

FINDINGS OF THE
RONGELAP RESETTLEMENT PROJECT
SCIENTIFIC STUDIES

EXECUTIVE SUMMARY REPORT
AND
TECHNICAL APPENDICES

BY THE
SCIENTIFIC MANAGEMENT TEAM

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DATE:

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SCIENTIFIC MANAGEMENT TEAM meeting with the Rongelap community on Mejatto, February 1994.

[left to right: SMT member Steven L. Simon; consultant to Diet Study, Dorothy Mackerras; SMT Chairman, Kieth Baverstock; SMT member, Bernd Franke, RRP Administrative Director, James Matayoshi (standing)].

Photo by Hiromitsu Toyosaki.

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RONGELAP RESETTLEMENT PROJECT

Report of First Phase:

**Determining Compliance with Agreed Limits
for Total Annual Dose-rate on Rongelap Island and
Actinide Contamination of Soils
on Rongelap Islands and Neighbouring Islands**

by

Scientific Management Team

**April 1994
Revised November 1994**

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Executive Summary

Herein is described the results of a comprehensive radiological survey of Rongelap Island to determine its compliance with agreed limits on annual dose-rate to residents subsisting on a "local food only" diet, and americium and plutonium concentrations in soil, under the terms of the Memorandum of Understanding reached between the Departments of Interior, and Energy of the United States of America and the Republic of the Marshall Islands and the Local Government of the Rongelap Atoll and signed on 21 February 1992. The present report is a non technical summary based upon seven detailed appendices carrying the detailed results of the survey.

Summary and Recommendations

Given the terms and conditions of the MoU we find that the predicted dose-rate and soil concentration of actinides are out of compliance on Rongelap Island and the neighbouring islands but that they could be met, under the terms of the MoU, by appropriate remedial action making the island safe for rehabilitation.

We recommend that:

- Urgent consideration should be given, in close consultation with the Rongelap community and their representatives, to agreeing measures to reduce the level of caesium in the local food diet and to providing, through other measures, support to eliminate the need to gather food from the more contaminated regions in the atoll.
- In the light of information being gathered on the micro-distribution of actinides in soil and on the degree to which children ingest soil, consideration should be given, again in close consultation with the Rongelap community, to measures to reduce the availability of actinides for incorporation into the body.
- In all above considerations careful attention should be paid to the need to ensure that the Rongelap community is comfortable with the safety of their islands as a future home for them and their children in perpetuity. The need to offset the loss of well-being incurred by past uncertainties concerning the radiological status of their homelands should be given a high priority when exploring with the Rongelap community solutions to redress the radiological status of their islands.

Scientific Management Team

Keith F Baverstock (Chairman)
Bernd Franke
Steven L Simon

April 1994 (revised November 1994)

1. Introduction

1.1 Scope and Purpose of the present report

This report is intended to be a non technical summary of the objectives, methodologies, results and implications of the first phase of the Rongelap Resettlement Project. It is backed by seven technical appendices describing in detail the methods employed and the results obtained.

1.2 Historical perspective

On 21 February 1992 a Memorandum of Understanding was reached between the Republic of the Marshall Islands Government, the Rongelap Atoll Local Government, the US Department of Energy (Office of Environment, Safety and Health) and the US Department of the Interior (Office of Territorial and International Affairs). The agreement enacted two radiological limits which must be in compliance before resettlement of Rongelap should take place. These are:

- An annual dose, over and above that from natural background radiation, of 100 mrem assuming that the diet consists of only locally produced foods, and
- A surface concentration of plutonium and other transuranic elements of $0.2 \mu\text{Ci}/\text{m}^2$ which was translated by the DoE to 17 pCi/g averaged over the top five centimetres of the soil.

The purpose of the first phase of the Rongelap Resettlement Project is to determine whether either of the limits will be exceeded on Rongelap Island and the neighbouring southern islands in the Rongelap Atoll.

1.3 Summary of the strategy employed

1.3.1 Criteria for compliance

The above limits are framed in the MoU in deterministic terms, i.e. that no one will exceed the 100 mrem/year compliance limit and that at no point on the island will the 17 pCi/g compliance limit for actinides in the top 5 cm of soil be exceeded. In the case of both limits determinism is inappropriate since there are no circumstances in which their being exceeded could be excluded entirely. In practice there will be a distribution of doses and activity concentrations within the population from which either a probability that an individual or location will exceed the limit, or a proportion of the population or locations exceeding the limit, can be derived.

In order to overcome this difficulty we propose to re-define the criteria for the limits being exceeded in probabilistic terms as follows:

- The limit will be deemed exceeded if 1% or more of the population or locations exceed the compliance limits, or an individual or location has a 1% or more chance of exceeding the compliance limits.

The 100 mrem/year limit is taken to include all sources of exposure other than natural background radiation, i.e. external radiation from nuclides in the terrestrial environment and internal radiation derived from locally produced foods. In practice the dominant contributor to both will be caesium-137 (^{137}Cs) in the soil and transferred to the food chain. Other nuclides, e.g. americium-241 (^{241}Am) and cobalt-60 (^{60}Co) contribute to external exposure and strontium-90 (^{90}Sr) contributes to internal exposure. In the following dose rates from ^{137}Cs have been calculated and the additional contribution from other sources estimated.

1.3.2 Determining compliance

Natural background radiation from external sources is low in coral atolls due to the lack of minerals in the terrestrial environment. Never-the-less, direct measurement of external exposure with, for example, an ionisation counter, would entail subtracting a component for natural background. Direct measurement of ^{137}Cs allows the direct determination of exposure from fallout.

The following integrated strategy has been adopted:

- *in situ* measurements of the gamma spectrum one metre above the ground and at 200 m intervals over Rongelap Island have been made with a germanium detector and count rates for ^{137}Cs and ^{60}Co determined from the spectra.
- Four grid squares were selected, two in the vicinity of the main settlement (where soil disturbance was likely) and two remote from it, and within each 25 further measurements were made.
- Determinations of the distribution of ^{137}Cs with depth in the soil have been made at 12 of the 63 locations measured.
- ^{137}Cs , ^{60}Co , ^{241}Am and plutonium-239,240 ($^{239,240}\text{Pu}$) have been determined from a composite of three 15 by 15 by 5 cm deep samples taken within 15 m of each *in situ* measurement.
- ^{137}Cs has been measured in samples of foodstuffs at a relatively small number of locations primarily to confirm the much more comprehensive measurements of food samples by DoE. Intercomparisons have justified the use of those data.
- Maps of ^{137}Cs count rates ($S(x)$) and total Pu and Am concentrations in soil have been prepared by interpolation from the sample points.
- By application of the "radii of utilisation" maps of Cs count rate in soil averaged over radii of 200, 500 and 1000 m ($T_R(x)$) have been derived.
- ^{137}Cs count rates have been converted, with the help of the soil profile data, to ^{137}Cs concentrations in soil and compared with the soil determinations.
- Plant:soil transfer factors have been derived from measured concentrations in vegetation and soil and supplemented by earlier data collected by the DoE and the distribution of values computed.
- Doses from external exposure have been derived from the ^{137}Cs in soil values and measurements of ^{60}Co and ^{241}Am for a series of "radii of utilisation" and conditions of living (i.e. time out of doors, on lagoon etc.).

- A survey of the diet of the residents of Mejjatto has been carried out and the distribution of caloric intakes and the contributions from local and imported foods determined. (Since 1985 Mejjatto Island on Kwajalein Atoll has served as the home of the relocated Rongelap community).
- Following consultation with the Rongelap communities in Mejjatto, Majuro and Ebeye, the local food only diet to be used in dose assessment has been agreed.
- Doses from internal exposure have been derived from the local food only diet and based on the measured energy intake distribution for the Mejjatto community and the derived soil transfer factors for ^{137}Cs .
- Estimates of internal exposure to other nuclides (about 2% of total internal dose) are based on earlier measurements by the DoE.
- Concentrations of plutonium in bone tissue were measured in deceased residents of Rongelap.
- Historic whole body counting data for Rongelap residents between 1958 and 1985 were analysed.
- No account has been taken of doses from inhalation or from the drinking of well water where the contributions to total dose rate are expected to be very tiny.

Initial measurements of ^{137}Cs count rates showed significant variation of ^{137}Cs in soil across the island which may indicate either differences in the retention of Cs in the soil, perhaps due to variations in the organic components of the soil or disturbance (leading to burial) of the Cs in the soil. Given such variations, doses will depend to some degree on patterns of behaviour of the inhabitants. To incorporate this aspect we have employed the "radius of utilisation", R, calculating doses for values ranging from 100 m to 1 km. Surveys of behaviour by interview with the community on Mejjatto and through observation and interview on an outer island have been made in order to justify the choice of "R".

1.3.3 Rationale for constructing ^{137}Cs count rate and actinide concentration maps

Measurements made at discrete locations either by soil sampling or gamma spectroscopy are subject to two kinds of error, namely the measurement error and the error due to having sampled only a small area, a few hundreds of square cm in the case of a soil sample and about 100 square metres in the case of gamma spectroscopy. The mapping process interpolates between sampling points to derive a smooth surface, using adjacent points on the sampling grid to help reduce the sampling error term. As such this process "averages" to some degree and so narrows the distribution of concentrations when compared to the distribution of measured values. This process has the effect of improving confidence in the extreme ends of the distribution of count rates.

2. Methodology

2.1 Measurements of external exposure (see Appendix A3)

Hyperpure germanium detectors were used for all spectrometric measurements both *in situ* and in samples taken of soils and vegetation for laboratory analysis .

All *in situ* measurements were made according to the method of Beck et al. (1972)¹ and interpreted by their methods as well as by those described by Jacob and Paretzke (1986)². Laboratory detectors were calibrated by standard procedures and verified by a five laboratory international intercomparison study.

In situ measurements were made at 63 locations on a 200 m grid over the island (see figure 2.1) and at 100 locations within four 200 m grid squares at 40m spacing. These values were used to construct maps of count rate, $S(x)$, by interpolation between points on the grid matrix and maps of count rate averaged over various radii, $T_R(x)$ (see Appendix A3).

Count rate in the full energy peak is dependent on the vertical profile of activity in the soil due to scattering of photons from deeply buried activity. Soil profiles to a depth of 30 cm (6 increments by 5 cm depth each) were taken in order to correct for this effect.

Three soil samples were taken within 15 m of the sites of each *in situ* measurement, packed, dried and counted under standardised conditions in the laboratory.

⁶⁰Co and ²⁴¹Am also make a contribution to external dose and measurements of the count rates in the ⁶⁰Co and ²⁴¹Am full energy peaks were also made .

Conversion factors for corrected count rate to exposure rate were taken from Beck (1972) and for exposure rate to dose rate from ICRP Publication 51³.

2.2 Measurement of internal exposure

Levels of caesium contamination of vegetation depend on the soil concentration of Cs and to a lesser extent, the plant species. The ratio plant:soil for ¹³⁷Cs has been determined for a number of local food types, the most important of which is the coconut. Although there is considerable variability from sample to sample a value of 0.2 for both the liquid and solid components of the drinking coconut is representative with 50% of all samples within a factor two above and below. Calculation 2 uses probability distributions using data from this and other studies. The data acquired in this study have been supplemented by earlier data collected on Rongelap by DoE.

¹Beck, H. L., DeCampo, J. and Gogolak, C. 1972 *In situ* Ge(Li) and NaI(Tl) Gamma-ray Spectrometry. HASL-258 Health and Safety Laboratory, US Atomic Energy Commission.

²Jacob, P. and Paretzke, H. G. 1986 Gamma-ray exposure from contaminated soil. *Nuclear Science and Engineering*, 93, 248-261.

³ICRP Publication 51, 1989 Data For The Use In Protection Against External Radiation *Annals of the ICRP*, 20 (2).

The dietary survey yielded a distribution of energy intakes for the Mejjatto population which was corrected as described in the section on the Dietary Survey to reduce the overdispersion due to the use of single 24 hour recall data set. Body mass and height data were recorded in the dietary survey. Basal metabolic rates were estimated from the relationship of Schofield et al.⁴

2.3 Diet survey (see Appendices A4)

For more than 100 years, the Marshallese diet has consisted of a mixture of imported and local foods. From the periods of the occupations by Germany in the mid-1800s, the Japanese, and finally the Americans, the Marshallese people have subsisted on varying types and quantities of imported food as an adjunct to their abundant but monotonous marine-based diet. As atoll dwellers [and not agriculturists] the Marshallese and other people living in Pacific atolls have the most restricted diet of all oceanic peoples.

A local food only diet cannot be measured directly since there appears to be no population in the Marshall Islands which subsists for prolonged periods of time on a diet consisting of entirely local food items with no consumption of imported foods. Even if one were to conduct a dietary survey on more traditional islands, the problem would remain how to substitute imported food items, such as instant noodles or rice, with local food items.

The dietary survey was designed to satisfy two requirements of the dose calculation, namely to provide a distribution of energy intakes and to indicate the nature of the local food in the current diet on Mejjatto.

A 24-hour recall survey was chosen to give an estimate of the mean intake of nutrients and energy. Given the small size of the Mejjatto population and the desirability of including everyone in the survey, a single 24-hour recall was collected from all Mejjatto residents. Heights and weights of the population were taken as an external validity check of the mean energy intakes. A repeat survey of women 18 years and older was conducted.

Training was given to twelve volunteers of the Mejjatto community during a five day workshop in Majuro. The training program ensured that the interviewers understood the objectives of the dietary survey; had a rounding in basic nutrition relevant to the Marshall Islands' food culture; developed skills in interviewing techniques; were able to use common food utensils and food models to elicit amounts of food eaten by interviewees; were able to fill-in the dietary questionnaire; and understood the importance of the dietary survey in relation to the Rongelap Resettlement Project as a whole. A detailed description of the diet survey questionnaire, the use of utensils, food models and measures, the recipes and the process of data collection can be found in Appendix A4.

Dietary data was collected from 319 residents, with a repeat 24 hour recall of 48 women 18 years and over, several days after the first recall. The survey was planned so that interviews were spread evenly over the different days of the week, and so that interviewers carried out their

⁴Schofield, W. N., Schofield, C. and James, W. P. T., 1985 Basal metabolic rate - review and prediction, together with an annotated bibliography of source material. Human Nutrition: Clinical Nutrition 39C(Suppl 1) 1 - 96.

interviews in at least two households each day, and attempted to interview a mixture of men, women and children each day. The age and sex distribution of those interviewed is shown in Table 1.

Table 2.1 Description of population and measurements obtained

Age-sex grouping	Weight data	Height data	Diet data	Repeat diet data
Males				
< 5 yr	20	14	30	-
5 - 9 yr	28	28	33	-
10 - 17 yr	36	35	42	-
18 - 60 yr	51	51	62	-
>60 yr	3	3	6	-
Females				
< 5 yr	17	12	26	-
5 - 9 yr	26	26	30	-
10 - 17 yr	22	22	26	-
18 - 60 yr	48	54	54	42
>60 yr	8	10	10	6

The data from the survey were analyzed using the Nutritionist IV version 2.0 database. For nutrient information on local foods such as coconuts, the 1983 South Pacific Commission tables were used.

The data for mean energy intake (EI) as well as consumption of protein, carbohydrates and fat are commensurate with reference data (ICRP Publication 23). The average protein intakes of men and women are higher than the US Recommended Dietary Intakes whereas the energy intakes are slightly lower. Intake rates for males are higher than for females.

Table 2.2 provides an analysis of the observed energy intake rates in comparison with the estimated basal metabolic rate. The observed mean energy intake for men and women of 1.6 times the estimated mean basal metabolic requirement (BMR_{est}) is consistent with sedentary-light activity. The distribution is over-disperse with a small number of individuals reporting energy intakes below their estimated basal metabolic rate, whereas the maximum reported energy intake would be equivalent to unrealistically high physical activity levels.

Since annual mean values for energy intake are needed for the dose assessment, the variation in intake is described by a lognormal distribution of the ratio of EI/BMR_{est} whereby the standard

deviations of the natural logarithm of the mean m is adjusted such that the 1st percentile of the distribution is equivalent with a ratio of $EI/BMR_{est} = 1$. Since very heavy physical activity is associated with an average daily energy intake of 2.3 EI/BMR_{est} for males and 2.0 for females, the 99th percentile reflects reasonable upper limits of EI/BMR_{est} .

Table 2.2 Energy Intake (EI) compared to the estimated basal metabolic rate (BMR_{est})

Parameter	Boys 10-17 yr (N=35)	Girls 10-17 yr (N=22)	Men 18+yr (N=53)	Women 18+yr (N=41)
observed data:				
EI/BMR_{est} , avg	1.6	1.7	1.7	1.4
EI/BMR_{est} , min	0.46	0.69	0.59	0.72
EI/BMR_{est} , max	2.4	2.5	3.5	2.3
$m(EI/BMR_{est})$	0.41	0.51	0.45	0.33
$s(EI/BMR_{est})$	0.33	0.32	0.39	0.28
adjusted data:				
$m(EI/BMR_{est})$	0.41	0.51	0.45	0.33
$s(EI/BMR_{est})$	0.18	0.22	0.19	0.14
EI/BMR_{est} , 01-percentile	1.0	1.0	1.0	1.0
EI/BMR_{est} , 50-percentile	1.5	1.7	1.6	1.4
EI/BMR_{est} , 95-percentile	2.1	2.6	2.3	1.8
EI/BMR_{est} , 99-percentile	2.3	2.8	2.4	1.9

A local food only diet was derived using the following principles:

- Energy intake derived from measured energy intakes of the Mejatto community.
- Items available on Rongelap and providing a good balance of nutrients.
- The selection of food items not be biased by availability or non-availability of radionuclide data on the food item.
- Diet determined in consultation with local community.

With the endorsement by the Rongelap communities, the following diets were selected:

(#1) "Mejatto observed"

The current level of local food items as observed in the Mejatto survey (about 18% of total energy intake)

(#2) "Mejatto scaled"

Imported food items are replaced by local food items on a calorie-by-calorie basis in

in the same proportions as these local food items were consumed in the mean on the same proportions as these local food items were consumed in the mean on Mejjatto during the survey.

(#3) "Mejjatto scaled with rice"

same as #2 but accounting for the same mean rice consumption as observed on Mejjatto (between 25% and 30% of total energy intake).

(#4) "Naidu et al., scaled"

Imported food items are replaced by local food items on a calorie-by-calorie basis in the same mean proportions as these local food items were reported in the Naidu et al. survey.⁵

(#5) "Naidu et al., scaled with rice"

same as #4 but accounting for the same mean rice consumption as observed on Mejjatto (between 25% and 30% of total energy intake).

Table 2.3 provides a nutritional analysis of the selected diets.

In addition, calculations of local food consumption in between the intake observed on Mejjatto and a 100% level were requested by the communities. However, the Diet #2 ("Mejjatto scaled") was endorsed as the basis for the dose assessment.

2.4 Determination of actinides in soil (see Appendix A6)

Concentrations of ²³⁹Pu and ²⁴⁰Pu and ²⁴¹Am were determined in pooled samples (15 by 15 cm by 5 cm deep) taken at three points within 15 m of the site of each of the *in situ* spectroscopic measurements. Americium concentration was determined by laboratory gamma spectroscopy measurements of the 59.5 keV emission. Plutonium was determined radiochemically using microprecipitation onto a neodymium fluoride substrate followed by alpha counting with passively implanted silicon detectors. This technique was verified by interlaboratory comparisons with laboratories in New Zealand, Germany and the USA.

Interpolation maps similar to those prepared for the ¹³⁷Cs were prepared for actinides.

Calculation of total dose from ¹³⁷Cs (see Appendix A5)

This calculation has been carried out in duplicate at two separate locations (Majuro, RMI and Sussex, UK) with entirely independent programming and according to the same protocol as described in detail in Appendix 4 but with some small differences in approach. This was done to ensure that the final result contained no artifacts of programming or misinterpretations of the primary data.

⁵ Naidu, J.R., et al. Marshall Islands: A study of diet and living patterns. Brookhaven National Laboratory, Upton, N.Y. July 1980. BNL 51313

Table 2.3 Key data for diet models to be used in Rongelap compliance assessment
(data for females >18 yr; data for males >18 yr)

Diet	#1	#2	#3	#4	#5
Parameter	Mejatto	Mejatto scaled w/o rice	Mejatto scaled with rice	Naidu et al. scaled w/o rice	Naidu et al. scaled with rice
Total Energy Intake	1,900	1,900	1,900	1,900	1,900
(kcal/d)	2,750	2,750	2,750	2,750	2,750
Energy Intake from	18%	100%	75%	100%	75%
Local Foodstuffs	17%	100%	70%	100%	70%
(Percent)					
Energy Intake from Rice	25%	0%	25%	0%	25%
(Percent)	30%	0%	30%	0%	30%
Protein Intake (g/d)	72	82	71	100	87
	110	130	110	150	120
Carbohydrate Intake (g/d)	260	140	210	180	240
	360	130	260	260	360
Fat Intake (g/d)	67	120	92	80	61
	95	200	130	120	83

Dose from ^{137}Cs arises from two sources, namely external, from the radionuclide in the soil, and internal, from the nuclide transferred from the soil to the food chain either directly from the consumption of leaves, vegetables and fruit or indirectly from locally grown animals such as pigs, chickens and coconut crabs. Both components depend upon the concentrations of ^{137}Cs in soil. Soil concentration can be inferred from measurements of the count rate of ^{137}Cs as measured with a high resolution gamma spectrometer *in situ* under standard conditions (height above the ground etc.) when allowance has been made for the burial of the Cs in the soil. Burial has the effect of scattering radiation thus reducing the contribution to count rate in the unattenuated energy band or full energy peak for the nuclide.

The external component of dose rate depends on the extent to which an individual moves around the island, particularly if the count rate varies markedly from one part of the island to another. A relatively immobile individual will have an exposure rate typical of the locality in which he or she spends most time whereas a mobile individual will approximate to the average exposure rate

for the island. This "mobility" factor is allowed for in the "radius of utilisation" and is used in the mapping procedure to convert the $S(x)$ maps to $T_R(x)$ maps. Because the construction of the $S(x)$ map involves interpolation between points on the 200m grid, the dispersion of values of $S(x)$ over the island is narrower than that for the original measurements (the interpolation is in effect an averaging process over the order of distance equal to the grid spacing) and averaging over greater distances to construct $T_R(x)$ maps further narrows the distribution towards the average. Calculation 1 uses the $S(x)$ and $T_R(x)$ maps (for $R=500$) whereas calculation 2 is based upon the measurements without interpolation or averaging.

The internal component depends upon diet and the extent to which it includes contaminated local foods. Caesium transfer is not highly selective and uptake from the soil depends on factors such as the depth distribution of the Caesium in the soil in ways that are not fully understood. The ratio between Cs in vegetation and soil is termed the plant:soil transfer factor. Calculation 1 uses a single value of 0.2 and applies a sensitivity analysis in order to assess the dependence of total dose on this factor which lies in the range 0.1 to 0.4. Calculation 2 uses probability distributions using data from this and other studies. In both cases the soil concentration is the reference for calculating exposure so food gathered in a particular locality will reflect the caesium activity in the soil at that location.

Both the external and internal dose rates depend on body mass. In the external case dose rate is derived from exposure rate using standard ICRP conversion factors⁶. For internal exposure dose rate will depend upon energy intake, diet, and body mass. A diet survey of the inhabitants of Mejatto was used to assess the contribution of local foods to the present diet and to assess the distribution of energy intakes. The fractions of time spent in different activities was based on previous DoE assumptions.

Dose was calculated according to the protocol given in Appendix A2. There are a number of ways of carrying out this calculation. In selecting the method used we were mindful of the need to use a method that was readily comprehensible as well as reliable. The approach has been to calculate only the contribution from ^{137}Cs , using sensitivity analyses to determine whether or not the calculation is "robust" to reasonable uncertainties of fluctuations in values. Dose rate distributions have been computed for men and women separately (i.e., for the community of men or women, not for individuals). Dose to children was dealt with by comparison of energy intakes in relation to body masses. Dose distributions were derived using a Monte Carlo technique, drawing at random from the distributions of soil concentration, body mass and energy intake and in calculation #2, plant:soil concentration ratios as well. Reference is then made to the assumed diets. #1 representing the measured Mejatto diet, #2 the "local foods only diet" agreed with the Rongelap community and 3 other derived diets.

⁶ICRP Publication 51 Data For The Use In Protection Against External Radiation Annals of the ICRP, 20 (2), 1989.

4. Results

4.1 Total Dose Rate

Results are calculated as cumulative dose rate distributions under differing sets of assumptions. For simplicity they are presented herein as tables giving the annual dose rate for various percentiles (from 5th to 95th).

The results of calculations are given in tables 4.1 and 4.2 for men and women respectively. Calculation 1 is based on the $T_{500}(x)$ map and a single value of the plant:soil concentration ratio (= 0.2). Calculation 2 is based on the distribution of measured values of ^{137}Cs count rate and uses probability distributions for the plant:soil transfer factors for different plants. As anticipated the dispersion of the distribution based on $T_{500}(x)$ (calculation 1) is narrower than calculation 2 due to the greater degree of spatial averaging involved. Conversely, calculation 2 is broader due to the greater dispersion of the measured values and has a higher mean value due to the use of individual values for the plant:soil ratio which are generally higher than the "base value" of 0.2 used in calculation 1.

Table 4.1 Dose rates⁷ (mrem/year) for men over the age of 18

Percentile	Calculation 1			Calculation 2		
	Diet #1	Diet #2	Diet #3	Diet #1	Diet #2	Diet #3
5	17.5	59.5	44.5	8.9	40.2	32.1
25	20.5	72.5	54.5	20.3	85.7	67.2
50	22.5	85.5	63.5	28.4	124.8	94.5
75	25.5	101.5	74.5	36.7	168.4	121.5
95	30.5	130.5	95.5	52.5	280.6	173.8

Table 4.2 Dose rates⁸ (mrem/year) for women over the age of 18

Percentile	Calculation 1			Calculation 2		
	Diet #1	Diet #2	Diet #3	Diet #1	Diet #2	Diet #3
5	17.5	54.5	43.5	8.6	36.2	30.3
25	20.5	67.5	53.5	19.2	76.2	61.1
50	22.5	78.5	61.5	28.2	108.0	86.8
75	25.5	91.5	71.5	36.2	149.6	101.2
95	29.5	114.5	88.5	49.8	216.1	152.5

⁷Developments in geostatistical modelling presently in progress will lead to changes in the results of calculation 1. In general the distribution for $S(x)$ will be broadened and shifted to somewhat higher values. Spatial averaging of the results of calculation 2 may lead to a narrowing of the distribution.

⁸see note 7

4.2 Dose from other radionuclides

External exposure due to ^{60}Co and ^{241}Am will increase the external component by about 1%. Strontium-90 may add a further 2% to the internal dose. Actinides, due to their very limited uptake into the plants, contribute a few percent to internal dose.

4.3 Dose to Children

The smaller body mass of children potentially exposes them to greater doses than adults. It can be demonstrated that although the dose per unit intake is higher for children than adults by a factor 1.4 to 1.5 for the 6 to 10 year old, the energy intake more than compensates, such that under identical exposure conditions the ^{137}Cs doses to small children are typically 54% of those to adult males and 74% of the adult female values.

For young children the intake of actinides from direct ingestion of soil has yet to be examined but is unlikely to add much to the dose. It should, however, be examined as an issue in its own right.

4.4 Actinide concentrations in soil

On Rongelap Island 1.1% (2/175) of the measured values for Am and Pu exceed the compliance limit of 17 pCi/g. The interpolation map was not used in the context of compliance since the requirement is to ensure that there are no points with measured values above the limit. The map does, however, help to locate those regions of the island that have consistently high values. For neighbouring islands, measurements indicate 14% (6/43) of measurements fail to comply with the limit.

5. Discussion

5.1 Total annual dose rate

The results indicate that, on the basis of ^{137}Cs exposure alone, between 25 and 75% of male members of the Rongelap community would exceed the compliance limit of 100 mrem/year while living a traditional outer island lifestyle and consuming a local food only diet. The internal dose dominates. The additional contribution from ^{60}Co and ^{241}Am to external exposure is small, perhaps of the order of 1% of that from ^{137}Cs . Strontium-90 contributes to internal exposure and may be expected to increase the internal component of dose by 2%. It is noted that calculation 2 yields somewhat higher doses and has a wider dispersion of values. This is because of the higher plant:soil ratios used and the fact that the underlying distributions are lognormal. Estimates of radiation doses made from whole body counting data of former residents of Rongelap Atoll during the years 1958 to 1985 indicate that if the same diet and food collection patterns applied now, as then, with a mixture of local and imported foods, a small fraction of the population would be above the 100 mrem/year compliance limit.

It should be noted that all calculations are based on the local food being gathered from Rongelap Island. The traditional food gathering islands lie in the north of the atoll and are more, and in

some cases considerably more, contaminated than Rongelap Island. The effect of gathering food from these islands would be much the same as increasing the value of the plant:soil ratio. We consider it unreasonable to assume that in practice the gathering of food from these islands, particularly in times of water and food shortages, can be effectively prohibited.

As stated earlier, attention has been concentrated on ^{137}Cs because of its dominance and because it is possible to reduce exposures by practical measures. There is for example considerable scope for reduction of the internal component by treating growing areas with potash fertilizer⁹. A reduction by a factor four, which can be achieved by this technique, will more than halve the total dose values bringing almost all the population within the 100 mrem/year compliance limit on the basis of a local food only diet. The consumption of imported foods will reduce doses further.

However, we believe more extensive measures than potash fertilisation are called for. The 100 mrem/year (1mSv/year) limit is widely¹⁰ regarded as the limit of acceptability for public exposure to ionising radiation, for practices which give rise to exposures in addition to those arising from natural and medical exposures, although it is generally accepted in radiological circles that the health impact of such exposures is small. Public concern for health detriment, real or imagined, is in itself a health detriment when health is viewed in its widest sense, that is, including loss of well-being as a detriment. Thus measures which reduce the likelihood that community members would exceed the compliance limit would serve to minimise the detriment caused by concern for their health.

In the case of the Rongelap community the most likely contributing factor to increasing dose will be the need to visit the northern islands at times of food and water shortages. Measures to ensure adequate water and food supplies on Rongelap Island, such as ground or ocean water purification and the capability to refrigerate and store protein foods, are examples of measures that contribute in that direction. We recommend that careful consideration is given to this type of mitigation in close consultation with the Rongelap community.

5.2 Actinide contamination of soil

While the failure to comply with the limit on Rongelap Island is marginal it has to be acknowledged that there is more concern worldwide about exposure to actinides than other forms of radioactivity. Given that many of the measured values are close to the limit we believe it worthwhile to take some remedial measures, especially to reduce the possibility of intakes by young children ingesting contaminated soil. Measurements are in progress to determine the micro-distribution of the actinides which will assist in determining the best strategies for remedial action but we have in mind the provision of, for example, radiologically clean coral to provide actinide free surfaces around houses and in community areas. The study of plutonium in

⁹Robison, W. L. and Stone, E.L. 1992, The effect of potassium on the uptake of ^{137}Cs in food crops grown on coral coals: coconut at Bikini Atoll, Health Physics 62, 496-511.

¹⁰ 1mSv/year is the ICRP recommended public dose limit for planned exposures when averaged over a lifetime. It should be noted that implicit in this figure is the assumption that societal benefit is derived from the activities that lead to this exposure. In the case of the exposures from living on Rongelap the exposed community derives no benefits.

bone from exhumed Rongelap residents does not indicate that the actinides are readily transferred to man, even as children. On the basis of these measurements the contribution to the 100 mrem/year limit is about 1%.

The compliance limits are clearly exceeded on the neighbouring islands and attention will have to be given to remedial measures appropriate to the use to which these islands will be put.

6. Summary and Recommendations

Given the terms and conditions of the MoU we find that the predicted dose-rate and soil concentration of actinides are out of compliance on Rongelap Island and the neighbouring islands but that they could be met, under the terms of the MoU, by appropriate remedial action making the island safe for resettlement.

We recommend that:

- Urgent consideration should be given, in close consultation with the Rongelap community and their representatives, to agreeing measures to reduce the level of Caesium in the local food diet and to providing, through other measures, support to eliminate the need to gather food from the more contaminated regions in the atoll.
- In the light of information being gathered on the micro-distribution of actinides in soil and on the degree to which children ingest soil, consideration should be given, again in close consultation with the Rongelap community, to measures to reduce the availability of actinides for incorporation into the body.
- In all above considerations careful attention should be paid to the need to ensure that the Rongelap community is comfortable with the safety of their islands as a future home for them and their children in perpetuity. The need to offset the loss of well-being incurred by past uncertainties concerning the radiological status of their homelands should be given a high priority when exploring with the Rongelap community solutions to redress the radiological status of their islands.

APPENDIX A1

MEMORANDUM OF UNDERSTANDING

English language version

Kajin Majol version

February 1992

MEMORANDUM OF UNDERSTANDING

by and between

THE REPUBLIC OF THE MARSHALL ISLANDS,
THE RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL,
THE UNITED STATES DEPARTMENT OF ENERGY
OFFICE OF ENVIRONMENT, SAFETY AND HEALTH

and

THE UNITED STATES DEPARTMENT OF THE INTERIOR,
OFFICE OF TERRITORIAL AND INTERNATIONAL AFFAIRS

for the

RONGELAP RESETTLEMENT PROJECT

February 1992

MEMORANDUM OF UNDERSTANDING

by and between

THE REPUBLIC OF THE MARSHALL ISLANDS,
THE RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL,
THE UNITED STATES DEPARTMENT OF ENERGY
OFFICE OF ENVIRONMENT, SAFETY AND HEALTH

and

THE UNITED STATES DEPARTMENT OF THE INTERIOR,
OFFICE OF TERRITORIAL AND INTERNATIONAL AFFAIRS

for the

RONGELAP RESETTLEMENT PROJECT

This MEMORANDUM OF UNDERSTANDING (hereinafter referred to as "MOU"), is made by and between the REPUBLIC OF THE MARSHALL ISLANDS (hereinafter referred to as "RMI"), the RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL (hereinafter referred to as "RALGOV"), the UNITED STATES DEPARTMENT OF ENERGY represented by the Office for Environment, Safety and Health (hereinafter referred to as "DOE/ES&H"), and the UNITED STATES DEPARTMENT OF THE INTERIOR represented by the Office of Territorial and International Affairs (hereinafter referred to as "DOI/OTIA").

WITNESSETH:

WHEREAS, the purpose of this MOU is to implement provisions of Title I, Sections 103(i) and 105(c) of U.S. Public Law 99-239; and

WHEREAS, in furtherance of the foregoing provisions of U.S. Public Law 99-239 and Nitijela Resolution 1986-62, RMI and RALGOV have caused to be prepared the "Rongelap Atoll Resettlement Project Scientific Work Plan", a copy of which is attached hereto (and hereinafter referred to as the "Rongelap Work Plan"); and

WHEREAS, in furtherance of the foregoing provisions of U.S. Public Law 99-239, the U.S. Congress has appropriated funds for the implementation and support of the Rongelap Work Plan pursuant to Public Law 102-154; and

WHEREAS, RMI and RALGOV have agreed to and shall by a future separate agreement establish a Rongelap Resettlement Project (hereinafter referred to as the "Rongelap Resettlement Project") in order to fully implement and assure the day-to-day management of the scientific studies and conduct other resettlement activities; and

WHEREAS, all the parties to this MOU are committed to taking all actions required in order to assure the timely implementation of the Rongelap Work Plan and such future resettlement activities and actions as may subsequently prove necessary such that the resettlement of the people of Rongelap may be secured;

NOW THEREFORE, be it agreed as follows:

ARTICLE I - GENERAL

Agreement generally by and between the signatory parties:

1. The activities of the Rongelap Atoll Resettlement Project Scientific Work Plan, otherwise referred to herein as the "Rongelap Work Plan", are hereby endorsed by each of the signatory parties as the proper scientific studies that are necessary to characterize the radiological and environmental conditions of the southern islands of Rongelap Atoll, and upon which the determination for resettlement of the southern islands will be made and further that:

2. The signatory parties commit themselves, one to the other and each to all, that upon receipt of funding for the Rongelap Work Plan pursuant to U.S. Congressional appropriation they shall fully cooperate in and support the completion of the Rongelap Work Plan and the studies undertaken pursuant thereto.

ARTICLE II

AGREEMENT BY AND BETWEEN DOI/OTIA AND DOE/ES&H, RALGOV, AND RMI FOR THE IMPLEMENTATION AND CONDUCT OF THE RONGELAP WORK PLAN IN SUPPORT OF THE RESETTLEMENT OF THE PEOPLE OF RONGELAP

The Department of Interior/Office of Territorial and International Affairs, the Department of Energy/Office of Environment, Safety and Health, the Rongelap Atoll Local Government Council on behalf of the People of Rongelap, and the Republic of the Marshall Islands further agree that:

[The initial stage - Determination of readiness for resettlement]

1. The study and ultimate resettlement of Rongelap shall be undertaken in stages, beginning with an initial environmental and radiological assessment of Rongelap Island and those islands comprising the southern one-half of Rongelap Atoll, said area to encompass on the western side of Rongelap Atoll from Bokonlep Island south and on the eastern side from Erebot Island south.

2. The primary condition of a determination to initiate resettlement for the area defined in Section 1 of this Article is that the calculated maximum whole-body radiation dose equivalent to the maximally exposed resident shall not exceed 100 millirem (mrem)/year above natural background, based upon a local food only diet, such that if the radiological assessment undertaken in accordance with the Rongelap Work Plan demonstrates that no individual would receive an annual radiation dose equivalent in excess of 100 mrem above natural background, resettlement will ensue. RALGOV may at its discretion give consideration to additional potential measures (i.e., application of fertilizers) to reduce individual and population radiation exposures to the returning population further below the 100 mrem/year limit.

3. The "local food only diet" declaration is meant to constitute a traditional Rongelapese diet consisting of local food taken, grown and/or gathered from the southern islands of Rongelap Atoll and the immediately surrounding waters as defined in Section 1 of this Article. It is agreed that the makeup of a Rongelap "local food only diet", and for comparison purposes a more "realistic diet", shall be more precisely determined and quantified pursuant to the Rongelap Work Plan, in consultation with the Rongelap community. In its determination of what constitutes a "local food only diet", the Rongelap Atoll Local Government Council may at its discretion include imported foods that are staples of the diet, e.g. rice.

4. (a) An additional condition of mitigation is the extent of transuranic contamination, especially plutonium contamination of soil. The parties are agreed that this issue, as well as the possible need for an environmental cleanup program solely for transuranic contamination, requires careful deliberation. To this end, it is agreed that the studies undertaken pursuant to the Rongelap Work Plan shall include measurements of transuranics in the environment of Rongelap Atoll, utilizing as an action limit the screening level of the U. S. Environmental Protection Agency ("EPA") of 0.2 microcuries per square meter, which has been translated by the DOE/ES&H into an activity concentration of 17 picocuries/gram (pCi/g) of transuranics averaged in the top 5 centimeters (cm) of soil. The action limit has been set at 17 pCi/g of transuranics in soil. Measurement of transuranic contamination in the environment and determination of whether the action limit has been met or exceeded will be made pursuant to an appropriate environmental sampling plan developed by the Rongelap Resettlement Project.

(b) Should the Rongelap Work Plan investigations determine that no soil concentration of transuranics is in excess of the aforementioned prescribed action limit, then no further consideration for soil clean-up of transuranics is warranted. If, on the other hand, it is determined that soil concentrations exceed the prescribed action limit, then recommendations as to the need for remedial activity and/or clean-up shall be included as part of the report prepared pursuant to the Rongelap Work Plan.

(c) To the extent that transuranic contamination exists in excess of the prescribed action limit but is limited in nature, controllable, and does not impact designated dwelling, food gathering, food growing, and/or recreational areas, then resettlement may ensue while mitigative measures are considered and/or undertaken.

5. In the event the assessment of Rongelap Atoll conducted pursuant to the Rongelap Work Plan demonstrates that radiological conditions on Bokonlep Island or Erebot Island (and their immediate waters) exceed the herein-defined standards for resettlement, the overall determination to initiate resettlement for the southern islands of Rongelap Atoll shall be made without consideration of, and to the exclusion of, radiological conditions on Bokonlep Island or Erebot Island.

[A determination of non-readiness for resettlement]

6. In the event that the environmental and radiological assessment undertaken pursuant to the Rongelap Work Plan demonstrates that the southern islands of Rongelap Atoll are not ready for resettlement without first undertaking a clean-up and remedial program, the Rongelap Resettlement Project shall immediately prepare a report for presentation to the parties hereto containing recommendations as to clean-up requirements and optional remedial activities designed to make the southern islands of Rongelap Atoll ready for resettlement.

[Need for further surveys]

7. (a) In the event the Rongelap Work Plan report(s) to be prepared by the Rongelap Resettlement Project in accordance with Article III, Section 6(a) of this MOU demonstrate(s), based upon the standards and criteria herein set forth,

(1) that the southern islands of Rongelap Atoll are fully resettlable, the second stage of project study shall be the radiological characterization of the northern islands of Rongelap Atoll; or, alternatively,

(2) that the southern islands of Rongelap Atoll are not fully resettlable without remedial activity and/or clean-up, even after consideration of Section 5 to this Article, then the Rongelap Resettlement Project shall immediately propose for consideration by the parties an extended environmental radiation characterization necessary to support the development of remedial actions and/or clean-up, as prescribed by Section 6 of this Article, environmental radiation characterization in such other areas as Rongerik Atoll and Ailinginae Atoll and further, upon completion of these objectives, the Rongelap Resettlement Project would proceed with the evaluation of the northern islands of Rongelap Atoll as prescribed in subsection 7(a)(1).

(b) It is the intent of the parties to ensure that appropriate environmental and radiological assessments are ultimately conducted of all of the ancestral homeland of the Rongelap people to include the remainder of Rongelap Atoll, Ailinginae Atoll, and Rongerik Atoll. It is understood that these additional studies contemplated by this section are subject to and conditioned upon future U.S. Congressional funding.

[Resettlement]

8. Rongelap community resettlement will ensue if the initial assessment described at Section 1 of this Article establishes that no individual residing on the southern islands of Rongelap Atoll and consuming a local food only diet would receive a calculated dose of 100 mrem/year or more of radiation above natural background in the Marshall Islands.

9. Once a determination of readiness for resettlement by the Rongelap Resettlement Project is made and affirmed by the parties to this MOU, planning for resettlement and implementation thereof shall immediately commence, with the full cooperation of all parties to this MOU. It is the understanding and expectation of the parties that funding for rehabilitation and resettlement shall be provided by way of separate U.S. Congressional appropriation, the funds to be transferred from the U. S. Government to a Rongelap Resettlement Trust Fund in accordance with the trust agreement between DOI, RMI, and RALGOV for utilization consistent with this section and any conditions or requirements imposed by Congress.

10. For purposes of resettlement, "Rongelap community resettlement" refers to the voluntary return to Rongelap Atoll of the Rongelap people now residing on Mejjatto Island and such other citizens of the Marshall Islands who by virtue of their land rights in Rongelap Atoll voluntarily wish to be resettled.

11. The parties recognize that health concerns may exist for many members of the Rongelap community by virtue of their prior exposure to radiation. Additionally, they recognize the need for continued radiological monitoring both of returned citizens and of the Rongelap Atoll environment upon resettlement. Accordingly, the parties agree to address these problems as part of the resettlement program.

12. The parties also agree that in the event of a determination for resettlement and subsequent resettlement, relevant revisions to recommended individual exposure levels as expressed in International Commission for Radiation Protection ("ICRP") and National Council on Radiation Protection and Measurements ("NCRP") guidelines will be reviewed to ensure that radiation exposures are maintained at an acceptable level of risk.

[Future]

13. If in the future applicable radiation protection standards (e.g., the NCRP and the ICRP) are significantly reduced to below current recommendations, or post-resettlement whole-body measurements indicate that Rongelap residents are being exposed to radiation levels in excess of the 100 mrem/year limit established by Section 2 of this Article, then the parties agree to reevaluate the individual doses being received by the population or an individual at that time to determine that no individual is being exposed to any undue risk, and take such remedial action as shall at that time be deemed appropriate.

ARTICLE III

AGREEMENT BY AND BETWEEN THE RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL (RALGOV) AND THE REPUBLIC OF THE MARSHALL ISLANDS (RMI)

The RALGOV and RMI further agree that:

1. In order to facilitate the implementation of this MOU and the Rongelap Work Plan, RALGOV and RMI shall establish a separate entity, to be known as the Rongelap Resettlement Project, which shall serve as the contracting authority for implementation of this MOU and the Rongelap Work Plan, and which shall be governed jointly by one representative of RMI and one representative of RALGOV.

2. The scientific direction and operational management of the Rongelap Resettlement Project shall be delegated by RMI and RALGOV, through the Rongelap Resettlement Project, to a Rongelap Resettlement Project Scientific Management Team (hereinafter the "Scientific Management Team"). In addition to his/her duties and obligations as set forth in Section 3 of this Article, one member of the Scientific Management Team, mutually selected by RMI and RALGOV, shall serve as principal scientific advisor to the Rongelap Resettlement Project.

3. The Scientific Management Team shall be selected by RMI and RALGOV and be comprised of not less than two nor no more than three appropriately qualified scientists. The members of the Scientific Management Team shall be assigned joint responsibility for the scientific direction and operational management of the Rongelap Resettlement Project, notwithstanding that their respective duties and responsibilities under the Rongelap Work Plan may vary. At least one of the scientists shall have demonstrated expertise in environmental and radiological analysis. Upon appointment of the scientists comprising the Scientific Management Team, RMI and RALGOV shall through the Rongelap Resettlement Project provide a service contract for each individual's term of appointment.

4. RMI and RALGOV shall utilize such funding as is made available by the Government of the United States, pursuant to Congressional appropriation, and the assistance of the RMI Nationwide Radiological Study pursuant to Article VI, paragraph 7 of this MOU and Article II, Section 1(e) of the Agreement Between the Government of the United States and the Government of the Marshall Islands for the Implementation of Section 177 of the Compact of Free Association ("the Section 177 Agreement"), to fulfill the scientific and technical requirements of the Rongelap Work Plan as well as the reporting requirements that are mandated by this MOU.

5. The RALGOV and RMI shall also mutually establish and contract for a Rongelap Resettlement Project Scientific Peer Review Group (hereinafter the "Scientific Peer Review Group"), to provide scientific peer review of the implementation of the Rongelap Work Plan and other technological aspects of the conduct of the Rongelap Resettlement Project. The Scientific Peer Review Group shall be available for consultation to the Scientific Management Team as necessary to execute the Rongelap Work Plan. The RALGOV and RMI may upon

mutual agreement change membership on the Scientific Peer Review Group as resettlement proceeds, and needs dictate.

6. (a) The RALGOV and RMI shall charge the Scientific Management Team with the responsibility of providing the following reports, in both English and Marshallese, to the Rongelap Resettlement Project established pursuant to Section 1 of this Article:

(1) On or before May 1, 1992, a preliminary report on the readiness of the southern islands of Rongelap Atoll for resettlement in order to permit the parties to decide whether to pursue the study option set forth at Section 7(a)(2) of Article II of this MOU in preference to the option described at Section 7(a)(1).

(2) Upon conclusion of the Rongelap Work Plan, a comprehensive report, in both English and Marshallese, shall be prepared on the radiological conditions on Rongelap Island and the southern islands of Rongelap Atoll, pursuant to such requirements and such schedules as may subsequently be deemed necessary by RMI and RALGOV. Said report shall address each component of the Rongelap Work Plan, any necessary and appropriate recommendations following therefrom, and shall include: a summary of study results; dose to infants and children; dose assuming a local food only diet; a comparison and analysis of the dose assuming a "local food only" diet as compared to a "realistic diet" that includes imported foods; and dose due to plutonium.

(b) Upon conclusion of subsequent stages of the Rongelap Resettlement Project, comprehensive reports shall be prepared pursuant to such requirements and schedules as may subsequently be deemed necessary by RMI and RALGOV.

7. Upon receipt of a Scientific Management Team report pursuant to Section 6 of this Article, the Rongelap Resettlement Project shall provide copies of same to the Scientific Peer Review Group for review, comment and recommendation. Resulting recommendations of the Scientific Peer Review Group shall be formally accepted or rejected by the Rongelap Resettlement Project.

8. RALGOV and RMI shall, through the Rongelap Resettlement Project, forward any report received pursuant to Section 6 of this Article to the parties to this MOU. Reports forwarded to the DOE/ES&H shall be accompanied by any comments and/or recommendations thereon received from the Rongelap Resettlement Project Scientific Peer Review Group.

[Assurance of future funding]

9. RALGOV and RMI hereby commit and pledge to one another that in the event the findings, conclusions and recommendations resulting from the Rongelap Work Plan warrant additional U.S. Congressional funding -- for further studies, clean-up and remedial programs, and/or for resettlement of the Rongelap people -- they will diligently and in good faith work together to obtain the additional Congressional appropriations and funding required.

10. RALGOV and RMI agree to do everything within their respective powers to maintain the scientific integrity of the studies and assessments undertaken pursuant to the Rongelap Work Plan, and to report in writing any compromise thereof to the other parties to this MOU.

ARTICLE IV - DEPARTMENT OF ENERGY, OFFICE OF ENVIRONMENT,
SAFETY AND HEALTH (DOE/ES&H)

The DOE/ES&H further agrees that:

1. The DOE/ES&H shall cooperate with and support the Rongelap Resettlement Project, specifically the Rongelap Work Plan, as requested and to the extent feasible, by providing whenever possible during the execution of its routine biannual environmental monitoring missions such logistical and other support as is mutually agreed, that will assist the Rongelap Resettlement Project in transporting necessary personnel and equipment to and from Rongelap Atoll.

2. Subject to modifications as the parties to this MOU might in the future agree, and Congress might subsequently endorse, DOE/ES&H shall continue the conduct of its bioassay and medical missions for the Rongelap people during and after resettlement of Rongelap, pursuant to Section 103 (h)(1) of Public Law 99-239.

3. Copies of reports received pursuant to Article III, paragraph 8 of this MOU shall be transmitted by DOE/ES&H to the NAS Scientific Peer Review Group for review and comment.

4. The DOE/ES&H shall give due consideration to the recommendations of its scientific peer review group (NAS). DOE/ES&H shall also assure all communications and recommendations by the NAS scientific peer review group are forwarded to RALGOV and RMI, for transmittal to the Rongelap Resettlement Project Scientific Peer Review Group.

5. Upon request by the Rongelap Resettlement Project and/or the Rongelap Project Scientific Management Team, DOE/ES&H shall furnish requested data relevant to the successful implementation and completion of the Rongelap Work Plan to the Rongelap Resettlement Project.

6. The DOE/ES&H agrees to conduct its Rongelap Atoll scientific activities and studies in a manner best calculated to complement and support the Rongelap Work Plan and the Rongelap Resettlement Project. To this end, DOE/ES&H shall regularly consult with the Rongelap Resettlement Project, the Rongelap Scientific Management Team, and other appropriate RALGOV and RMI representatives as to planned and ongoing DOE/ES&H or DOE/ES&H-contracted projects and activities related to or otherwise affecting Rongelap.

7. The DOE/ES&H shall provide or make available to RALGOV, RMI, the Rongelap Resettlement Project and/or the Scientific Management Team, without charge, requested declassified information, documents and data in DOE's possession, or under its custody or control, concerning past atmospheric and

terrestrial measurements relevant to the resettlement of the Rongelap people. To the extent if any documents of established relevancy are found to be classified, DOE/ES&H shall, upon request, immediately initiate a classification/declassification review in order to ensure, to the maximum extent possible, full disclosure of all information relevant and necessary to the Rongelap Resettlement Project and successful completion of the Rongelap Work Plan.

ARTICLE V - RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL (RALGOV)

The RALGOV further agrees that:

1. As set forth in Article II of this MOU, RALGOV agrees on behalf of the People of Rongelap that if the initial environmental and radiological assessments of the areas described in Section 1 of Article II establishes that no individual resettling to the southern islands of Rongelap Atoll and subsisting on a local food only diet would receive an annual radiation dose exceeding 100 mrem/year above natural background or would be incidentally exposed to concentrations of transuranics in the soil in excess of the prescribed action limit of 17 pCi/g, Rongelap community resettlement will ensue without consideration for mitigation. However, consideration may be given by RALGOV to additional potential measures (i.e., application of fertilizers) to reduce individual and population radiation exposures to the returning population further below the 100 rem/year limit.

2. RALGOV shall support the timely completion of the Rongelap Work Plan through:

(a) Making the RALGOV Members available to confer with the Scientific Management Team upon request;

(b) Securing any necessary permissions for access, entrance, and the conduct of the Rongelap Work Plan from individuals that may be required so that the Rongelap Resettlement Project can undertake and complete all project field work;

(c) Serving as a liaison between the Scientific Management Team and the Rongelap community at large;

(d) Providing local personnel and community support as necessary to accomplish the objectives of the Rongelap Work Plan and any forthcoming approved activities related to resettlement.

ARTICLE VI - REPUBLIC OF THE MARSHALL ISLANDS (RMI)

RMI further agrees that:

1. The Rongelap Resettlement Project and Rongelap Work Plan shall be undertaken in conjunction with the RMI Nationwide Radiological Study conducted pursuant to Article II, Section 1(e) of the Section 177 Agreement.

2. RMI shall, upon receipt of funds from the DOI/OTIA pursuant to this MOU, assure the availability of these funds to the Rongelap Resettlement Project within five (5) business days of receipt thereof, pursuant to the terms and conditions to be set forth in a separate agreement to be entered into and by and between the Rongelap Resettlement Project, RMI and RALGOV.

3. RMI assures that it will comply with all applicable U.S. Federal laws, regulations and requirements as they relate to the application, acceptance, use and accounting of funds provided pursuant to this MOU.

4. An SF-270, Request for Advance or Reimbursement, will be submitted by RMI to DOI/OTIA for release or drawdown of funds on a quarterly basis. Said Requests shall be made in consultation with, and pursuant to instructions received from the Rongelap Resettlement Project.

5. An SF-269, Financial Status Report, will be submitted by RMI to DOI/OTIA quarterly.

6. RMI shall provide copies of all Financial Status Reports and Requests for Advances or Reimbursements, and any other reports required pursuant to this MOU, the Rongelap Resettlement Project, which shall in turn make same available to the parties to this MOU on a quarterly basis.

7. Utilizing the funds made available to the RMI Government pursuant to Article II, Section 1(e) of the Section 177 Agreement, the RMI Nationwide Radiological Study shall contribute certain of its services to the Rongelap Reassessment Project.

8. RMI is to assure the clearing and maintenance of the air runway on Rongelap Island during the course of the Rongelap Resettlement Project sufficient to permit air traffic to and from Rongelap Island.

ARTICLE VII - DEPARTMENT OF THE INTERIOR,
OFFICE OF TERRITORIAL AND INTERNATIONAL AFFAIRS (DOI/OTIA)

The DOI/OTIA agrees that:

1. The DOI/OTIA shall transfer to the RMI the appropriate portion of such funds as are appropriated by the United States Congress, pursuant to the FY 1992 Appropriation Act (P.L. 102-154) for the Department of Interior for the purpose of implementing the Rongelap Resettlement Project/Rongelap Work Plan.

2. The appropriate portion of funds specifically appropriated by the U.S. Congress for the purpose of implementing the Rongelap Work Plan shall be transferred to the RMI on a quarterly basis pursuant to, and upon receipt by DOI/OTIA of a quarterly SF-270 Request for Advance or Reimbursement.

3. Copies of all financial status reports submitted to DOI/OTIA, and any other reports required to be submitted to DOI/OTIA by this MOU, shall be provided on a timely basis to all parties to this MOU.

ARTICLE VIII - ADDITIONAL AGREEMENTS

All parties further agree:

1. The Rongelap Resettlement Project shall be initiated on or about March 1, 1992, or as soon as practicable after funding is made available by the United States Government. It is the understanding and intent of the parties to this MOU that the Rongelap Resettlement Project shall conclude its mandate and submit its final report pursuant to the Rongelap Work Plan and this MOU on or before April 1, 1993.

2. This MOU shall remain in effect pending completion of the Rongelap Resettlement Project. This MOU may be amended by the mutual consent of the parties hereto.

3. This MOU shall be governed and interpreted in accordance with applicable laws of the United States and the Republic of the Marshall Islands. In the event of dispute with respect to the interpretation or execution of this MOU, the parties agree to in the first instance seek to resolve such dispute through good faith negotiations by and between themselves. Should such negotiations fail, resolution of the matter in dispute shall be governed by the Conference and Dispute Resolutions provisions of Title Four, Article II, of the Compact of Free Association, although nothing contained therein shall be construed as a bar to direct and immediate participation by RALGOV in any conference or dispute resolution activities thereunder.

4. Program Funding - The details of the levels of support to be furnished between DOE/ES&H and DOI/OTIA with respect to funding will be developed in specific interagency agreements or other agreements, subject to the availability of funds. This MOU shall not be used to obligate or commit funds or as the basis for the transfer of funds. The DOE/ES&H and the DOI/OTIA will provide each other mutual support in budget justification to the Office of Management and Budget and hearings before the Congress with respect to programs on which the organizations collaborate.

5. Management Arrangements - This MOU envisages direct communication between DOE/ES&H and officials of other organizations involved in managing the work to be performed. Interagency agreements or project plans will set forth specific arrangements for program implementation. Such plans set forth necessary cooperative arrangements and procedures for handling decisions required by various Government officials. Specific funding and tasking will be implemented through interagency agreements.

6. Public Information Coordination - Subject to the Freedom of Information Act (5 U.S.C. 552), decisions on disclosure of information to the public regarding projects and programs referenced in this MOU shall be made by DOE/ES&H or DOE/OTIA following consultation with the other parties representatives.

6. Amendment and Termination - This MOU may be amended by written agreement between the parties. This MOU may be terminated by the mutual

written agreement of the parties or by any party upon 45 day written notice to the other parties.

7. Effective Date - This MOU shall be effective upon the latter date of signature of the parties. It shall remain in effect for a 5-year term from the effective date.

APPROVED AND SO AGREED:

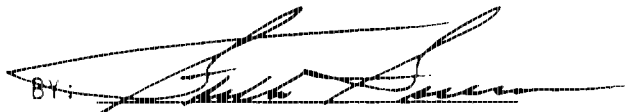
U.S. Department of Energy
Office of Environment, Safety
and Health

Date: 2/21/92

BY: 

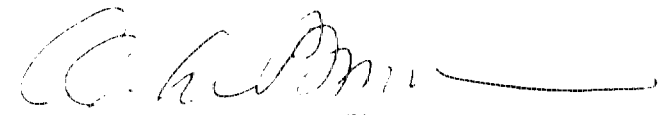
U.S. Department of the Interior
Office of Territorial and
International Affairs

Date: 2/21/92

BY: 


Republic of the Marshall Islands

Date: 2/21/92

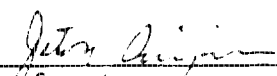
BY: 

Rongelap Atoll Local Government Council

Date: 2/21/92

BY: 
Mayor, RALGOV

Date: 2/21/92

BY: 
Senator

DRAFT

MEMORANDUM OF UNDERSTANDING

ikijien im ikotan

REPUBLIC OF THE MARSHALL ISLANDS,

RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL,

UNITED STATES DEPARTMENT OF ENERGY

OFFICE EO IKIJEN ENVIRONMENT, SAFETY IM HEALTH

im

UNITED STATES DEPARTMENT OF THE INTERIOR

OFFICE EO IKIJEN TERRITORIAL IM INTERNATIONAL AFFAIRS

kin

RONGELAP RESETTLEMENT PROJECT

MEMORANDUM OF UNDERSTANDING in (jen kio manlok naj na etan "MOU"), ej komon ikijien im ikotan REPUBLIC OF THE MARSHALL ISLANDS (jen kio manlok naj na etan "RMI"), RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL (jen kio manlok naj na etan "RALGOV"), UNITED STATES DEPARTMENT OF ENERGY eo ej jermal ikijien ej Office eo ikijen Environment, Safety, im Health (jen kio manlok naj na etan "DOE/ES&H"), im UNITED STATES DEPARTMENT OF THE INTERIOR eo ej jermal ikijien ej Office eo ikijen Territorial im International Affairs (jen kio manlok naj na etan "DOI/OTIA").

ILO KAMOLE:

EINWOTKE, un eo an MOU in ej non na kitien eon ko iloan Title I, Section 103(i) im 105(c) ilo U.S. Public Law 99-239; im

EINWOTKE, ilo an wor kitien eon ko iloan U.S. Public Law 99-239 im Nitijela Resolution 1986-62, emwij an RMI im RALGOV ketobrak "Rongelap Atoll Resettlement Project Scientific Work Plan" eo, copy eo an ej ekejel ijin (im jen kio manlok naj na etan "Rongelap Work Plan"; im

EINWOTKE, ilo an wor kitien eon ko ilo U.S. Public Law 99-239, emwij an U.S. Congress kejemoj money ko non jerbale im rie Rongelap Work Plan eo ekkar non Public Law 102-154; im

EINWOTKE, RMI im RALGOV rar erra im naj bar erra ibben dron kin juon kon eo tokelik non eiki Rongelap Resettlement Project eo (jen kio manlok naj na etan "Rongelap Resettlement Proejct") non lukkun jerbale im non kabin bwe bok edroin jerbale ekatak ko im menin jermal ko jet eierlok wot; im

EINWOTKE, aolep party ko ilo MOU in rej kalimur bwe renaj komone ijoko kunaier non lale im libjerjere Ronglap Work Plan eo bwe jermal ko air ilo ran ko tokelik en maron kalikar im kajejjet an armij in Rongelap bar jeblak;

KIO KIN MEN IN, ej bin bwe en einwot in:

ARTICLE I - GENERAL

Kon eo ikijien im ikotan party ko rej likit eltan peier:

1. Jermal ko an Rongelap Atoll Habitability Project Scientific Work Plan, ilo juon wewin bar na etan "Rongelap Work Plan", party ko jimor rej erra iben dron kaki ke ierkein rej jermal im makitkit ko rekkar non komoni ekatak ko im rej kalikar im jone radiological im environmental condition ilo turoktata in Rongelap Atoll, im bwe jermal im makitkit kein renaj kwalok jemlok eo elane ekkar im jejjet non bar jeblaklok non ene kein turoktata ilo Rongelap Atoll.

2. Party kein rej sign rej kalimur ibiermake, juon non eo juon im juon non aolep, bwe ilo an tokektok money ko ikijien Rongelap Work Plan eo ekkar non kejemoj ko an Congress eo an U.S. rej aikuij lukkun karejar ibben dron im jermal ibben dron bwe en dredrelok Rongelap Work Plan eo im ekatak im etali ko naj komoni ekkar non jimwe im jejjet ko air.

ARTICLE II

KON EO IKIJIEN IM IKOTAN DOI/OTIA IM DOE/ES&H, RALGOV, IM RMI
ILO LIBJERJERE IM KOMONE RONGELAP WORK PLAN EO
NON JIBAN BAR KEJEBLAK LOK ARMIJ IN RONGELAP

Department eo an Interior/Office eo ikijen Territorial im International Affairs, Department of Energy/Office eo ikijein Environment, Safety im Health, Rongelap Atoll Local Government Council ilo etan armij in Rongelap, im Republic of the Marshall Islands rej erra bwe:

[Ilo Jinoi - Etale bar Jeblaklok eo]

1. Ekatak im kin an lukkun komon jeblaklok eo non Rongelap ej aikuij in komon ilo lor jet buntan ne ko, jinoe kin environmental im radiological assessment ilo Rongelap Atoll im ene ko jet turoktata im rekabwe jimettan in Rongelap Atoll, jikin in ekitbuij iturilik in Rongelap jen Bokonlep iturok im iturear in Erebot turok.

2. Jonak eo non lale ekkar ke bar jeblaklok non ijekein konono kaki ej alikar ilo Section 1 ilo Article in

3. "local food only diet" ej melelein bwe mona in Majol ko ilo Rongelap rej mona jen i, kadroki im bokitok jen ene ko turoktata ilo Rongelap im mona ko jen lojet ko kemeleleiki ilo Section 1 in Article in. Ewor buru-wot-juon bwe wewin keboje mona in majol ko ilo Rongelap en tiljek komoni im en wor jonan mona jen i ekkar non Rongelap Work Plan eo ilo bok melele im kabilek jen community eo an Rongelap. Non lale mona rot rej mona in Majol, Rongelap, kin konan eo an, emaron bar kakobaiktok mona ko jen likin im emakijkiy im ekka wot mona jen i.

4. (a) Wewin eo ej aikuij driklok ej ikijien paijin ko rekajur einwot plutonium eo ilo bwidrej. Party ko aolep rej bar erra bwe katak kin paijin rot in im kab karreo eo ikijien bwirej rej aikuij in let im bolet komadmodi. Kin mein, ej weppen bwe karkan ekatak eo ilo Rongelap non bar lale jonan eo ilo bwidrej. Kajeon loor jonak ko an U.S. Environmental Protection Agency (EPA) eo im ej 0.2 microcuries juon square meter eo im DOE/ES&H ear likit ilo jonak ko an bwe en 1 microcuries/gram (PCI/g transuranics ilo bwidrej eo ilon im ej bed 5 centimeter. Jonan eo emwij karoke ej 17 pCi/g transuranics. Non kalikar jonan jorren eo ilo bwidrej im non lale jonan emon ak an bwidrej kein laplok air jorren naj walok jonak ier jen wot ekatak in.

(b) Elane ekatak in enaj lo ke ejelok bwidrej en elaplok jorren eo ie jen jonan eo ej kalikar ke erre, inem ejamin menin aikuij bwe kareo eo en komon. Botap, elane ej alikar ke jorren eo an bwidrej eo ella ion jonak eo emwij karoke, inem aikuij wor recommendation ko non rejan bwe en wor kareo im recommendation kein rej erom mottan report eo naj komon in Rongelap Work Plan eo.

(c) Elane enaj alikar ke jorren eo elaplok jen jonan eo karoke, ijoke ewor kile boprae an laplok im ebareinwot jab walok ijoko im aremij rej jokwe ie, ijoko mona ko rej edrek ie, ilo jikin ikkure ko, inem emaron wor bar jeblaklok, botap enaj wonmanlok wot komadmad ko non bukot kilen an driklok.

5. Elane enaj walok jen ekatak ko kin Rongelap ekkar non Rongelap Work Plan eo rej kalikar bwe jonan radiation ilo Bokonlep ak Erebot (im lojet eo ebake ir) elaplok jen jonak eo emon non jokwe ie, inem jemlok ak bebe eo eliktata ikijien bar jokwe ilo ene ko turoktata in Rongelap en jab komon ekkar non jonan radiation ko ilo Bokonlep ak Erebot.

[Jemlok eo ej kalikar bwe ejjab emon bar jeblaklok]

6. Elane ekatak ko ikijen environmental im radiological assessment ko emwij komoni ilo air ekkar non Rongelap Work Plan eo ej kalikar bwe ejjab emon bar jeblaklok non ene ko turoktata ilo Rongelap ilo an ejelok kareo im bar komon kajimwe, inem Rongelap Resettlement Project eo en komone juon report ilo ien eo emokajtata im kwalok non party kein im en wor ilo report eo recommendation ko ikijien kareo im wewin komoni kajimwe ko rekkar bwe en wor bar maron in jeblaklok non ene ko turoktata ilo Rongelap Atoll.

[Menin aikuij non bar komon ekatak]

7. (a) Elane Rongelap Resettlement Project eo enaj komoni report ko an ikijen Rongelap Work Plan eo ekkar non Article III, Section 6. (a) ilo MOU in rej kwalok kin wewin im unleplep kein ijin ilal,

(1) bwe ene ko turoktata ilo Rongelap Atoll remaron bar jeblaoklok non i, wewein eo tok juon ej non komoni ekatak ko non lale jonan radiation ilo ene ko tuiontata ilo Rongelap Atoll; or, elane jaab,

(2) bwe ene ko turoktata ilo Rongelap Atoll rejjab maron bar jeblaklok non i ilo an ejelok kajimwe ak kare-eo, mene emwij lori wewin ko rej walok ilo Section 5 ilo Article in, inem Rongelap Resettlement Project eo en ilo ien eo emokajtata kalikar non party ko kin bar kaitoklok ekatak eo ikijen jonan radiation non juon tere eo enaj dredrelok non komon bwe en wor bar komoni kajimwe ko ak kareeo ko, einwot an kemlet ilo Section 6 ilo Article in, im jonak radiation ilo jikin ko jet einwot Rongerik Atoll im Ailingae im bar wonmanlok kake, elane enaj dredrelok kotobar kein, Rongelap Resettlement Project eo emaron etal wot kin evaluation ko an ikijen ene ko tuiontata ilo Rongelap einwot an kemlet ilo subsection 7(a)(1).

(b) Ej kotobar eo an party kein non lale bwe wewin ko rekkar im jimwe ilo komoni ekatak ko kin environmental im radiological assessment ren dredrelok ilo jukjuk im amnak jolete ilo Rongelap im en bar kobatok ijoko jet rejanin dredrelok jerbali ilo Rongelap Atoll, Ailingae Atoll, im Rongerik Atoll. Ewor melele bwe ien komoni ekatak kein kemelet ilo section in rej wawa-wot ion karok ko im money jen U.S. Congress ilo ran ko tokelik.

[Bar Jeblaklok]

8. Jujjuk im bed eo ekel ilo Rongelap enaj lale bwe elane ekatak ko imantata einwot air walok ilo Section 1 ilo Article in rej kalikar bwe ejelok armij, ro rej jokwe ilo ene ko turoktata ilo Rongelap Atoll im rej mona mona-in Majol, en ej bok uno ko tarin 100 mrm ilo juon year ak laplok jen jonan eo emwij karoke non boke ilo Marshall Islands.

9. Ne ewor juon jemlok ebin non bar jeblak lok jen ibben Rongelap Resettlement Project im ejuburuon party ko iloan MOU in, karok ko ikijien bar jeblaklok im wewin libjerere ren mokaj im ijino, kin juon-wot buru ikotan party kein iloan MOU in. Ej melele eo in im kejatrikrik eo an aolep party kein bwe money ko non kakeik aikuij ko ikijien bar jeblaklok naj kawor-kitier jen U.S. Government non jermal ko an Rongelap Resettlement Trust Fund eo ilo an lor trust agreement eo ikotan DOI, RMI, im RALGOV bwe money kein ren jermal ilo an ejelok idabtok iben section in im aolep kon ak karok ko jet Congress eo an United States ear kakien kaki.

10. Non wot melelein bar jeblaklok, nan in "Rongelap community resettlement" ej melelein jabrewot armij in Rongelap eo ej jokwe kio ilo Mejato im jabrewot armij in Rongelap eo ewor an bwirej ilo Rongelap im ej bar jeblaklok non Rongelap Atoll kin konan eo an make.

11. Party kein jimor rej kile problem eo ikijen ejmour eo emaron walok non Rongelap community itok wot jen air kar baj naninmij mantak wot. Kobatok ibben men in, rej bar kile bwe emenin aikuij bwe en wor wot kakolkol non armij in Rongelap ro emwij air naj jeblaklok im jokwe. Inem kin menin, party kein rej juon-wot-buru ilo ereilok iloan problem in kin ejmour einwot ke ej mottan bar resettlement program eo.

12. Party kein rej juon-wot-buru bwe ilo ien eo ej wor bebe non bar rollok im jokwe, jonan level in naninmij eo ej walok ilo International Commission eo ikijien Radiation Protection ("ICRP") im ilo Antional Council eo ikijen Radiation Protection im Measurements ("NCRP") naj bar etali non lale bwe jonan level in radiation eo en bed wot ilo jonak eo ejimwe im jejjit.

[Ilju im Jeklaj]

13. Elane ilo ilju im jeklaj jonan radiation (non wanjonak NCRP im ICRP) elap jen jonan an driklok jen jonak eo kio, ak elane kakokol in enbwinin armij ro rej jokwe ilo Rongelap rej kwalok bwe jonan radiation elaplok jen 100 mrem ilo juon year einwot an kemlet ilo Section 2 ilo Article in, inem party kein rej juon-wot-buru im bar etali jonan uno ko armij ro rej boki ilo air bar jokwe ijen im rej lo bwe ejelok armij en enaj wor kauatata none, im aikuij komoni wewin ko rekkar non komon kajimwe ko.

ARTICLE III

KON EO IKIJIEN IM IKOTAN RONGELAP ATOLL LOCAL GOVERNMENT (RALGOV)
IM REPUBLIC OF THE MARSHALL ISLANDS (RMI)

RALGOV im RMI rej bareinwot erra bwe:

1. Non komon bwe en mokaj libjerjere jibarbar ko an MOU in im Rongelap Work Plan eo, RALGOV im RMI rej aikuij ejake juon maron

eo ejonolok, im naj na etan Rongelap Resettlement Project, eo enaj jermal einwot juon contracting authority non libjerjere MOU in im Rongelap Work Plan eo, eo im enaj aikuij bok an malim in komoni jermal ko jen ibben RMI im juon representative an RALGOV.

2. Repelten jermal im edroin jermal eo an Rongelap Resettlement Project ej aikuij in tellokin wot RMI im RALGOV, ilo etan Rongelap Resettlement Project, ilo an ilok repelten im edroin kein non juon management team eo na etan Rongelap Resettlement Project Scientific Management Team (jen kio manlok naj na etan "Scientific Management Team"). Ilo an kobalok iben jermal ko an jet einwot air elejrak ilo Section 3 ilo Article in, juon member jen Scientific Management Team eo, eo im kelet in jimor RMI im RALGOV, enaj jermal einwot juon principal scientific advisor non Rongelap Resettlement Project.

3. Scientific Management Team eo naj kelet in RMI im RALGOV im uaan en jab iietlok jen ruo ak lonlok jen jilu scientist ro elap air kabel. Naj bar kelet ro im relukkun ekkar non jermal in. Ijelokkin men ko kunan kajojo csientist rein, erwoj naj jermal ibben dron non libjorjore makitkit ko ilo project in. RMI im RALGOV jimor renaj lale bwe scientist rein en wor air contract in jermal.

4. RMI im RALGOV renaj kejerbal money ko kejemoj in kien eo an U.S. non jermal in, im jiban eo jen RMI National Radiological Study, ekkar non Article VI, 7 ilo MOU in im Article II, Section 1(e) ilo Compact in Free Association eo ikotan Kien eo an United States im Kien eo an Marshall na etan (Section 177 Agreement), eo ej ikijien non komoni ekkatak kein an scientist rein ikijien jermal eo ilo Rongelap im bareinwot kommon report ko kappe-in MOU in.

5. RALGOV im RMI rej jimor ejake im contract eo Rongelap Resettlement Project Scientific Peer Review Group (jen kio manlok naj na etan "Scientific Peer Review Group"), im jermal eo an ej non etale wonmanlok ko ilo jermal eo ion Rongelap im makitkit ko jet rejelet jeblak lok eo non ailin eo. RALGOV im RMI remaron ukot ro uaan Scientific Peer Group in jabrewot ien elane emenin aikuij bwe en eindrein.

6. (a) RALGOV im RMI renaj kemaron Scientific Management Team eo non an komon report ilo kajin belle im Marshall non kejelaik lok Rongelap Resettlement Project eo kin makitkit otemjej ekkar non karok ko ilo Section 1 in Article in:

- (1) Ilo ak mokta jen May 1, 1992, ej aikuij tobrak report eo imantata kin ene ko iturok in Rongelap Atoll non bar jeblaklok bwe en emman an party ko telokkier melele kin elane emenin ke aikuij non lor mokta option eo iumin Section 7 (a)(2) in Article 1 ilo MOU im jab option eo konono kake ilo Section 7 (a)(1).

- (2) Elane edredrelok jermal eo ion Rogelap, ej aikuij wor juon report ilo kajin belle im Marshall ikijien jonan radiation ilo Rongelap Island im ene ko turoktata ilo Rongelap Atoll, ekkar non karok ko aikuij lori einwot rej menin aikuij jen RMI im RALGOV. Report in ej aikuin in wor kemlet ikijien tibrikin katak eo; un ko ninnin im ajiri; drettan mona in Majol eo emwmij mona jene; jonak eo ikijen drettan mona in majol eo emwij mona jen e im keidi drettan eo na ibben jonan drettan mona eo boktok jen likin; im un ko ikijien plutonium.

(b) Elkin an dredrelok jermal ko an Rongelap Resettlement Project eo, report ko rej aikuij in dredrelok ekkar non men ko aikuij lori im karok ko im naj aikuij i jen RMI im RALGOV.

7. Elkin an wor report jen Scientific Management Team eo, ekkar non melele ko ilo Section 6 in Article in, inem Rongelap Resettlement Project eo enaj komon copy in report in im jilkinlok non Scientific Peer Review eo non aer ekatak kake im komon aer melele ikijien report eo im lellok non Rongelap Resettlement Project eo bwe en lale ej kweppene ke ak jaab.

8. RALGOV im RMI renaj jermal ibben Rongelap Resettlement Project in im jakemanlok juon report ekkar non Section 6 in Article in non party ko iloan MOU in. Report ko rej ilok non DOE/ES&H enaj bar ilok ibberlok elmkwot ak lemnak ko an Rongelap Resettlement Project Scientific Peer Review Group.

[Kakirmol kin Money ko Renaj Itok Ran ko Tokelik]

9. RALGOV im RMI rej jimor erra im kalimur ke elane tobrak ko, jemlok ko im bebe im lomnak ko renaj walok jen Rongelap Work Plan eo rej kwalok ke rej bar aikuij money jen U.S. Congress --- non bar komon katak, kareo im komon kajimwe, im/ak non bar kejeblaklok armij in Rongelap --- renaj ilo buru eo emol jermal ibben dron non ketobrak aikuij eo ikijen money jen Congress.

10. RALGOV im RMI rej erra bwe renaj lorlorjake ijoko kunaier ilo kejarok im tiljek kaki tokjen ekatak kein im jermal ko an Rongelap Work Plan, im report ilo jeje kin jabrewot bebe ko ikotair non party ko jet mottair ilo MOU in.

ARTICLE IV - DEPARTMENT OF ENERGY, OFFICE OF ENVIRONMENT, SAFETY AND HEALTH (DOE/ES&H)

DOE/ES&H rej bareinwot erra bwe:

1. DOE/ES&H enaj rerik im jiban Rongelap Resettlement Project kin emakit im jeblak eo, im elaptata Rongelap Work Plan eo, kin jona wot ijo remarone. Jiban ilo tore ko im rej komone kakolkol ko ilo melan ko, bokto-boktak menin aikuij ko im bar

makitkit ko jet einwot an kar kalimur bwe enaj jiban leto-letak armij im kein jermal non im jen Rongelap.

2. Wewin eo emaron oktak elane party ko iloan MOU in rej lo ke rekkar im Congress ej erra ilo jermal eo an DOE/ES&H ilo an komone jermal in kakilen armij ro ilo tore in im elkin aer jeblak non Rongelap, einwot an walok ilo melele ko ilo Section 103 (h)(1) ilo Public Law 99-239.

3. Ekkar non Article III paragraph 8 ilo MOU in ikijen report ko rej ilok non DOE/ES&H renaj ilok wot non Scientific Review Group eo bwe en lali im kwalok an lomnak ikijier.

4. DOE/ES&H naj aikuij komon an lomnak ikijien recommendation ko an Scientific Peer Review Group eo (NAS). DOE/ES&H ej aikuij in lorlorjake bwe aolep communication ko im recommendation ko an NAS scientific peer review group rej ilok non RALGOV im RMI, non air maron tobraklok iben Rongelap Resettlement Project Scientific Peer Review Group eo.

5. Elane ewor kajitok jen Rongelap Resettlement Project im/ak jen Rongelap Project Scientific Management Team, DOE/ES&H naj aikuij keboji jabrewot data ko kajitok kaki non wot bwe en dredrelok im tobrak jerbale Rongelap Work Plan eo im kwaloki lok non Rongelap Resettlement Project eo.

6. DOE/ES&H ej erra im komoni jermal ekatak ko kin Rongelap Atoll ilo wewin eo emon im jimwetata non kadredreiklok im jiban Rongelap Work Plan eo im Rongelap Resettlement Project eo. Ilo an komone wewin in, DOE/ES&H ej aikuij aolep ien kebaak im kejelaik Rongelap Resettlement Project eo, Rongelap Scientific Management Team, im dri utiej ro telokkier jen RALGOV im RMI ikijien jermal ko tellokin im ko ej lo bwe rekkar non an bar jibiwi im bareinwot project ko DOE/ES&H naj aikuij in contract i tok bwe ren jembali im remaron in naj jelet Rongelap.

7. DOE/ES&H naj aikuin kwalok non RALGOV, RMI, Rongelap Resettlement Project im/ak Scientific Management Team, ilo ejelok wonen, aolep melele ko rejjab menin nojak, im jabrewot log in jermal ko ibben DOE, ak iumin wonake eo an, ikijien aolep melele ko jen jinoim mantak non kalikar jonan ijo armij in Rongelap rebed ie. Elane ewor melele ko rej aikuij in bed wot ilo air nojak, inem DOE/ES&H enaj, elane ewor kajitok bwe en komone, komone juon ien etale non lale ta ej nojak ak ta ejjab menin nojak, bwe aolep melele kein ren maron in droijlok bwe en maron in dredrelok jibarbar im jermal eo an Rongelap Resettlement Project eo im Rongelap Work Plan eo.

ARTICLE V - RONGELAP ATOLL LOCAL GOVERNMENT COUNCIL
(RALGOV)

RALGOV ej bareinwot erra bwe:

1. Einwot an alikar ilo Article II ilo MOU in, RALGOV ej erra ilo etan armij in Rongelap bwe elane ekatak eo kin melan ko im drettan paijin eo einwot ej ailikar ilo Section 1 in Article II ej kwalo ke ejelok juon ian ro renaj jokwe ilo ene ko iturok im mona mona ko ie, enaj laplok radiation eo ibben jen 100 mrem ak jorren eo ilo bwidrej eo ej jab laplok jen jonnin in 17 pCi/g, inem lemnak eo non jeblak enaj ijino. Ijoke, enaj wor wot lomnak ko non bukot kilen bwe en driklok jona paijin eo jen 100 mrm iloan juon year.

2. RALGOV enaj lorlorjake bwe en dredrelok Rongelap Work Plan eo ilo ien eo emwij karoke bwe en dredrelok ie ilo an komoni wewin kein:

(a) Komon bwe en wor member in RALGOV rej kwelok ibben Scientific Management Team eo elane ewor kajitok bwe en eindrein;

(b) Kotlok ak lelok maron non droij-drelon ak etale jermal ko an Rongelap Work Plan eo ibben armij ro tellokier bwe kinke Rongelap Resettlement Project en etal wot im kadredreiklok aolep project ko an;

(c) Jermal ikotan Scientific Management Team eo im jukjuk im bed eo an Rongelap.

(d) Kabbok dri jermal jen jukjuk im bed eo im jiban jen armij ro ie einwot an naj menin aikuij non wot ketobrak jermal ko an Rongelap Work Plan eo im kab naj menin aikuij ak jermal ko jet naj aikuij non ketobrak jeblak lok in.

ARTICLE VI - REPUBLIC OF THE MARSHALL ISLANDS (RMI)

RMI ej bareinwot erra bwe:

1. Rongelap Resettlement Project eo im Rongelap Work Plan eo renaj wonmanlok ibben ekatak eo an RMI kin bar paijin kein einwot ej walok ilo Article II, SECTION 1 (e) ilo Section 177 Agreement eo.

2. Elkin wot an RMI ron ennan jen DOI/OTIA einwot melele ko ilo MOU in, inem enna enaj etal non Rongelap Resettlement Project eo iloan wot ran ko 5 elkin an walok ennan in. Jekjek in ej walok ilo juon kon ikotan Rongelap Resettlement Project, RMI im RALGOV.

3. RMI ej bareinwot erra ke enaj lori kakien ko an Federal ikijen kejerbal im leto-letak money ekkar non MOU in.

4. Juon Form in kajitok money (SF-270 Request for Advance ak Reimbursement) RMI enaj jilkinlok non DOI/OTIA bwe en itok money ilo kajojo kuata. Kajitok kin money naj aikuij in komon elkin bok an dron lomnak iben im ilo an ekkar non karok ko rej itok jen Rongelap Resettlement Project eo.

5. Juon Form (SF-269 Financial Status Report) RMI naj jilkinlok non DOI/OTIA ilo kajojo kuata.

6. RMI naj aikuij komon copy in report in makitkit ko an money im bareinwot copy in kajitok ko an ikijien money, im jabrewot copy in report ko im rej aikuij in wor ilo an ekkar non MOU in, non Rongelap Resettlement Proejct eo. Copy kein naj aikuij in bar komon an party ko rej bareinwot ekejel im mottan MOU in. RMI ej aikuij in komone wewin in ilo kajojo kuata.

7. Non kejerbal money ko rej walok ikijien Article II, Section 1 (e) ilo Section 177 Agreement eo ilo Compact in Free Association eo, Nationwide Radiological Study eo an RMI ej aikuij, ilo an wor lok kajitok non ibben jen Scientific Management Team eo, dror ijo kunan ikijen kein jerbal im dri jerbal kin drettan eo im aurokin etobar \$250,000 non jiban kadredreiklok jerbal eo an Rongelap Resettlement Project eo.

8. RMI ej aikuj lorlorjake bwe airport eo ilo Rongelap Atoll en errewo wot im tiljek non kejerbale ilo im toon wot an komon Rongelap Resettlement Project eo non wot itoitak jen im non Rongelap island ilo palun.

ARTICLE VII - DEPARTMENT EO AN INTERIOR,
OFFICE EO AN TERRITORIAL IM INTERNATIONAL AFFAIRS
(DOI/OTIA)

DOI/OTIA ej bareinwot erra bwe:

1. DOI/OTIA ej aikuij lelok non RMI drettan eo ekkar im jejjet ikijien money ko kejemoj in United States Congress, ekkar non Appropriation Act eo an FY92 (P.L.102-154) eo an Department of Interior non un ko ikijien jinoe Rongelap Resettlement Project eo im Rongelap Work Plan eo.

2. Drettan money eo ekkar im jejjet kejemoj in U.S. Congress non wot un eo non jinoe Rongelap Work Plan eo naj aikuij ilok non RMI ilo kajojo kuata ekkar non, im ilo an tokeklok ibben DOI/OTIA report eo ilo kuata otemjej na etan SF-270 Request for Advance or Reimbursement.

3. Copy in aolepen an kar money kein jerbal ko rej ilok non DOI/OTIA, im jabrewot report ko rej aikuij in ilok non DOI/OTIA ekkar non MOU in, naj aikuij ilok non aolep party ko iloan MOU in ilo ejelok rumij kaki.

ARTICLE VIII - KON KO JET

Aolep party kein rej erra bwe:

1. Rongelap Resettlement Project eo en ijino ilo ak iturinlok March 1, 1992, ien eo emokaj im melak elkin an alikar money jen Kien eo an United States. Ej melele eo in im jibarbar eo in an party kein ilo MOU in bwe Rongelap Resettlement Project eo en kejemlok eddo in an im komone report eo an eliktata ilo an ekkar non Rongelap Work Plan eo im MOU in ilo ak mokta jen April 1, 1993.

2. MOU in en bed wot im wor kitien mae ien eo ej jemlok im dredrelok Rongelap Resettlement Project eo. MOU in emaron in wor oktak ak kakobaba non e kin buru-wot-juon an aolep party kein ie.

3. MOU in ej wor kitien im melele ko iloan ren lori kakien ko rekkar im jejjet an United States im Republic eo an Marshall Islands. Ilo ien an wor oktak an dron lomnak ikijen melele in ak wewin kejerbal tokjen im kotobar ko an MOU in, inem party kein rej erra bwe wewin eo en komon imantata ej non bok im keidi an dron lomnak ikotair wot non dron. Elane ebin air bok an dron lomnak, inem wewin naj kejore aban in naj aikuij in komone ekkar non Conference im Dispute Resolution ko rej kemlet ilo Title Emen, Article II ilo Compact in Free Association eo, mene ejelok juon wewin einwot drolul in iekajet non komon bwe RALGOV en maron bok kunan ilo makitkit ko ilo Conference im Dispute Resolution eo.

4. Program Funding. Tibrikin drettan jiban ko jen DOE/ES&H im DOI/OTIA ikijen money enaj alikar ilo kon ko renaj komon ikotaier non dron, ekkar non jonan drettan money ko renaj alikar non komon bebe ikijier. MOU in enjab einwot juon menin kalimur ke enaj wor money ak einwot bar juon menin kadrelonlok money none. DOE/ES&H im DOI/OTIA renaj jimor jiban dron ilo komoni kajitok ko airro jimor ikijien budget non Office eo an Management im Budget im non ien ronjaki ko iman Congress ikijien program ko im rej tellokin ra kein ruo.

5. Management Arrangements - MOU in ej kile ke enaj wor kennanik dron ikotan DOE/ES&H im dri utiej ro ilo ra ko jet im ewor lok air ilo jerbali in. Kon ko ikotan agency kein non dron ak plan ko lomnak in jerbali naj kalikar ien jinoe jerbali kotobar ko an program in. Plan kein naj aikuij kalikar ta ko kunan agency kein im lajrak in kilen komoni jerbali kein non an dri utiej in dri kien ro komoni repelten im kilen jerbale program in. Wewin an money ko jerbali im oran dri jerbali im kein jerbali rej aikuij in alikar ilo kon ko rej komon ikotan agency kein.

6. Public Information Coordination - Ilo lor Freedom of Information Act (5 USC 552), maron eo non kadroijslok melele non public ikijen project im program kein ilo MOU in ej telokin DOE/ES&H ak DOE/OTIA elkin bok lomnak ko an party ko jet.

6. Amendment and Termination - MOU in emaron in oktak kin kon ko ilo jeje ikotan party kein. MOU in emaron in jemlok kitien kin kon eo erra ibben dron kake im ej walok ilo jeje im jen ibben jabrewot ian party kein ilo an komon kejela ilo jeje non party ko jet iloan 45 ran.

7. Effective Date - MOU in ej wor kitien ilo ran eo elkin ran eo party ko rej dror eltan peier ie. Ej aikuij bed wot im wor kitien iumin juon tere eo ej 5 year aitokan ijino jen ran eo ej wor kitien kon in ie.

APPENDIX A2

THE PROTOCOL BEING ADOPTED FOR ASSESSMENT OF RADIATION DOSES IN THE RONGELAP RESETTLEMENT PROJECT

M. C. Thorne

Revised 28 March 1994

**THE PROTOCOL BEING ADOPTED FOR ASSESSMENT OF RADIATION DOSES
IN THE RONGELAP RESETTLEMENT PROJECT, AS REVISED 28 MARCH 1994**

1. INTRODUCTION

Data arising from the various studies being undertaken as components of the Rongelap Resettlement Project (RRP) have to be interpreted in terms of the radiation doses that would be received by members of the Rongelap community following resettlement. This interpretation implies the application of a suitable dosimetric model and it is this model which is defined herein. The general requirements of the model are that:

- i) The quantities calculated shall be relevant to determination of compliance with the criteria set out in the Memorandum of Understanding;
- ii) The model shall make the most effective use possible of the data arising from RRP studies, and shall take into account other data of relevance, as appropriate;
- iii) The model shall be so structured that the views of the Rongelap Community on key issues can be properly taken into account;
- iv) The model and associated input data shall be documented in such a way that all the technical and social assumptions made in defining the assessment basis and undertaking the quantitative calculations are clearly and explicitly identified.

With respect to the quantities to be calculated, the Memorandum of Understanding provides quantitative compliance criteria relating to whole-body dose equivalent and to transuranic contamination of soil. These two criteria are essentially independent and the models proposed for evaluating compliance with them are described separately in Sections 2 and 3 below.

2. ASSESSING COMPLIANCE WITH THE CRITERION ON WHOLE-BODY DOSE EQUIVALENT

In the Memorandum of Understanding, it is stated that the primary condition of a determination to initiate resettlement is that the calculated maximum whole-body radiation dose equivalent to the maximally exposed resident shall not exceed 100 mrem y^{-1} (1 mSv y^{-1}) above natural background, based upon a local food only diet. The local food diet is to be a traditional Rongelapese diet consisting of local food taken, grown and/or gathered from the southern islands of the Rongelap Atoll and the immediately surrounding waters, and is to be defined in consultation with the Rongelap Community. Furthermore, in its determination of what constitutes a local food only diet, the Rongelap Atoll Local Government Council may, at its discretion, include imported foods that are staples of the diet.

It is also stipulated that, for comparison purposes, a more realistic diet shall be precisely determined and quantified.

In practice, the maximum whole-body radiation dose equivalent to the maximally exposed resident is not well defined, so the approach adopted is directed to assessing the distribution of individual doses which might be received by both external and internal exposure. This distribution can then be used to comment on whether a reasonable assurance of compliance with the criterion can be given. It is emphasised that the distribution of doses over the exposed population is more relevant, in public health terms, than is the dose to the maximally exposed individual. Furthermore, the distribution of individual doses provides a direct measure of the fraction of the population assessed as exceeding the criterion. This measure of compliance/non-compliance is not available if the assessment is based upon the characteristics of the maximally exposed individual.

Thus, the adopted model requires three components:

- i) A technique for computing the probability distribution function (pdf) for internal dose;
- ii) A technique for computing the pdf for dose due to external exposure;
- iii) A technique for combining the pdfs generated under components (i) and (ii).

These three components are specified below.

2.1 COMPUTATION OF THE PDF FOR INTERNAL DOSE

The internal dose derives primarily from ingestion of ^{137}Cs , but the methodology set out below allows the pdf of dose from ingestion of any other radionuclide to be computed similarly. For any one radionuclide:

$$D_{\text{int}} = QH \quad (\text{Eqn. 1})$$

where D_{int} (Sv y^{-1}) is the annual dose;
 Q (Bq y^{-1}) is the annual intake of the radionuclide; and
 H (Sv Bq^{-1}) is the dose per unit intake.

Values of H depend upon body mass and various other factors. Thus, for a particular individual:

$$H = f(m) + \epsilon \quad (\text{Eqn. 2})$$

where $f(m)$ is some function of body mass, at the time of intake; and
 ϵ is an uncertainty term representing the effects of other factors, e.g. variations in individual metabolism from the standard model used to compute $f(m)$.

In radiological protection, it is conventional to neglect the ϵ term and to take H as precisely determined by m (see, e.g. [1]). This is the approach adopted here, on the assumption that the criterion was originally set as a conventional dose limit. Thus, the assessment basis adopted is that:

$$H = f(m) \quad (\text{Eqn. 3})$$

Where a radionuclide is well retained in the body, $f(m)$ for juveniles may take into account the increase in body mass with age after the time of intake. In practice, the radionuclide of primary interest is ^{137}Cs . In this case, $f(m)$ varies to only a limited degree with body mass because of the longer biological half life of retention in individuals with larger body mass.

Values of Q are determined by the annual masses of foodstuffs consumed and the activity concentrations in them. Thus:

$$Q = \sum_i w_i C_i \quad (\text{Eqn. 4})$$

where w_i (kg y^{-1}) is the mass of foodstuff i consumed per annum; and C_i (Bq kg^{-1}) is the annual average concentration of the radionuclide in foodstuff i .

Both w_i and C_i will vary from individual to individual and it is proposed that this variation be taken into account in computing values of D_{int} .

Similarly:

$$r = \sum_i w_i q_i \quad (\text{Eqn. 5})$$

where r (kcal y^{-1}) is the annual calorific intake of an individual;
 w_i (kg y^{-1}) is as defined above; and
 q_i (kcal kg^{-1}) is the calorific content of foodstuff i per unit mass.

Equation 5 is conveniently rewritten as:

$$r = W \sum_i f_i q_i \quad (\text{Eqn. 6})$$

where W (kg y^{-1}) is the total mass of foodstuffs consumed per annum, i.e.

$$W = \sum_i w_i \quad (\text{Eqn. 7})$$

and:

$$f_i = w_i / W \quad (\text{Eqn. 8})$$

i.e. f_i is the fraction of the total mass of the diet contributed by foodstuff i .

From Equation 6:

$$W = r / \sum_i f_i q_i \quad (\text{Eqn. 9})$$

and

$$Q = r \sum_i f_i C_i / \sum_i f_i q_i \quad (\text{Eqn. 10})$$

Equation 10 is proposed as the basis for calculating Q values. In this expression, r and C_i are taken to be subject to uncertainty, q_i are taken as fixed values without uncertainty from standard dietary tables and f_i , the relative proportions of various foodstuffs in the diet, are taken to be defined in consultation with the Rongelap Community.

It is noted that m and r are likely to be quite strongly correlated. Thus, the overall procedure for computing a pdf for D is as summarised below.

- (i) Select a pair of values from the joint pdf on m and r using a Monte Carlo approach;
- (ii) Compute $H(m)$;
- (iii) Select a set of C_i values from the joint pdf on C , where C is the vector $(C_1, C_2 \dots C_i \dots)$;
- (iv) Compute Q using the well-defined f_i and q_i values together with the sampled values of r and C_i ;
- (v) Compute D_{int} ;
- (vi) Repeat steps (i) to (v) to generate a distribution of values of D_{int} ; i.e. a pdf of D_{int} .

Note that the pdf of D_{int} is conditional upon:

- (a) A deterministic model for dose per unit intake values given a specified body mass;
- (b) A diet fully characterised in terms of the relative proportions of the different foodstuffs, but not in terms of total annual mass of food ingested.

It is noted that several different dietary compositions, i.e. sets of f_i , may be used. These could comprise alternative versions of both the local food only and more realistic diet.

The origins of the various pdfs and other data required for the computational procedure set out above are summarised below.

- (i) The joint pdf on m and r will be derived from the dietary survey data collected as part of the RRP. In practice, data were obtained relating to $P(m, r')$, the joint probability density function on body mass and the daily calorific intake, r' . Transformation of $P(m, r')$ to $P(m, r)$ should take into account the greater degree of variability in r' than in r . This can be done by the use of physiological constraints on the distribution of r and/or by the use of data from repeat surveys.
- (ii) $H(m)$ will be computed directly from the age-dependent model adopted by the ICRP [1].
- (iii) Values of f_i will be proposed by members of the Oversight Committee working in conjunction with the Scientific Management Team, and will be refined and agreed in consultation with the Rongelap Community. Several sets of values may be adopted for both local food only and realistic diets, but two sets of values (one for a local food only diet and one for a realistic diet) will be identified as primary for compliance purposes. The other sets of values will be utilised to investigate the sensitivity of the results obtained to the relative dietary compositions adopted.
- (iv) Values of q_i will be taken from standard dietary tables. It is recognised that these values are subject to some uncertainty, but this is not large and is largely compensated for by using the same q_i values in calculating r' values in the dietary survey. It is also emphasised that pdfs for the q_i values are not readily available.
- (v) The joint pdf on C will be derived from the measured radionuclide concentrations in foodstuffs together with the estimated distribution of radionuclides in soils. The primary interest will be in ^{137}Cs and the approach adopted for this radionuclide is set out in detail below.

From the in situ gamma measurements, it is possible to predict the spatial variation of the count rate, $S(x)$, at any location x . Specifically, the predictor is chosen to minimize the mean-squared prediction error given the observations. The estimate of $S(x)$ is converted to an estimate of soil concentration, $C_s(x)$, on the basis of particular assumptions about the soil profile. Thus:

$$C_s(x) = \mu S(x) \quad (\text{Eqn. 11})$$

A limited number of soil profiles are available from various parts of the island and these may be used to compute a best estimate value of μ , μ , and an uncertainty, as reflected in the standard derivation of the measurements about μ , σ . As a basis for assessment, it is proposed that μ be used in Equation 11, but that the effects of varying μ over a reasonable range be explored in sensitivity studies.

For each foodstuff, i , the concentration in that foodstuff is taken to be given by:

$$C_i(x) = F_i C_i(x) \quad (\text{Eqn. 12})$$

where $C_i(x)$ is the concentration in foodstuff i ; and
 F_i is a soil:plant transfer factor for foodstuff i , which is assumed to be independent of location.

Values of F_i are to be calculated from observed values of C_i at specific locations together with estimated values of $C_i(x)$. Again, best estimate values of F_i are to be used for assessment purposes, with uncertainty in these values being taken into account in sensitivity studies.

For assessment purposes, it is appropriate to use spatial averages of $S(x)$, $C_i(x)$ and $C_i(x)$, rather than point estimates. For this reason, the following derived quantity is defined.

$$T(x) = (\pi R^2)^{-1} \int S(x-y) dy \quad (\text{Eqn. 13})$$

where the integration is over a disc of radius R , centred on the point x .

Various values of R are to be studied, to investigate the effects of different degrees of spatial averaging, but a single value should be agreed with the Rongelap Community as a basis for assessment.

Taking spatial averaging into account:

$$C_i(x) = F_i \mu T(x) \quad (\text{Eqn. 14})$$

2.2 COMPUTATION OF THE PDF FOR DOSE FROM EXTERNAL EXPOSURE

In this case, the primary determinants of dose are the ^{137}Cs concentrations in the areas utilised by the individual. These concentrations are reflected in the exposure rates in these areas. Overall:

$$D_{\text{ext}} = [f D_{\text{ext}}^{\text{res}} + (1-f) D_{\text{ext}}^{\text{util}}] \phi \quad (\text{Eqn. 15})$$

where D_{ext} (Sv y^{-1}) is the dose rate due to external exposure;
 f is the fraction of the time spent in residential areas;
 $D_{\text{ext}}^{\text{res}}$ (mR y^{-1}) is the average exposure rate in residential areas;
 $D_{\text{ext}}^{\text{util}}$ (mR y^{-1}) is the average exposure rate in utilised areas other than residential areas;
 ϕ (Sv mR^{-1}) is a conversion factor between exposure and whole-body effective dose equivalent.

Thus, the various potentially uncertain quantities associated with the calculation of D_{ext} are f , $D_{\text{ext}}^{\text{res}}$, $D_{\text{ext}}^{\text{util}}$ and ϕ . These are discussed separately below.

Values of f relate to the fraction of time spent within houses or in their vicinity. This fraction will differ from one individual to another, notably between men and women, and may well be different for children. However, relatively few data are available concerning this quantity and no data have been acquired specifically as part of the RRP. Since this is a behavioural matter, analogous to the selection of a particularly dietary composition, it is proposed that the Oversight Committee and Scientific Management Team determine a reference f value to be refined and agreed in discussion with the Rongelap Community.

It is assumed that individuals will utilise a variety of residential areas and that, in consequence, variations in D_{ext}^{res} between individuals will be only limited. In view of this, it is considered that the use of a single deterministic value of D_{ext}^{res} will not result in significant underestimation of variations in individual dose due to external exposure. However, it will be appropriate to comment on the sensitivity of the results obtained to different reasonable choices of f and D_{ext}^{res} . Furthermore, it is noted that D_{ext}^{res} should be based on values observed in residential areas on Rongelap at the present day. Specifically, no allowance should be made for the effects of development and reconstruction during any proposed reoccupation of the island. Qualitatively, such development and reconstruction is expected to reduce dose rates, but the degree of reduction cannot be quantified at this time.

Values of ϕ depend upon body mass. Thus, the appropriate approach is to select values of m from the pdf on m , $P(m)$ and then to calculate a value of ϕ .

The principal uncertainty is in D_{ext}^{uil} the mean exposure rate for an individual outside the residential area. The exposure rates have been demonstrated to vary substantially at different locations on Rongelap. However, individuals average out these variations to some extent by their utilisation of a spatially extensive resource area.

This is dealt with by utilising the spatially averaged in situ measurements defined in Equation 13. Thus:

$$D_{ext}^{uil}(x) = \eta T(x) \quad (\text{Eqn. 16})$$

where η is the conversion factor from count rate to dose rate. The value of η is weakly dependent upon the soil activity profile and the limited number of soil profiles available should be used to compute a best estimate value of η to be used as a basis for the assessment. Because the dependence of η on the soil profile characteristics is only weak, a sensitivity study varying η is not judged to be required.

Finally, it is proposed that the same samples of x be used in generating $D_{ext}^{uil}(x)$ as are used in generating $C_i(x)$ in Equation 14. Similarly, the values of m selected should be identical to those selected in solving Equation 3.

By using a Monte-Carlo approach, selecting multiple pairs of m and D_{ext}^{uil} as described above, and substituting into Equation 15, an appropriate pdf for D_{ext} is developed.

2.3 COMPUTATION OF THE PDF FOR TOTAL DOSE

The computations described in Sections 2.1 and 2.2 result in pdfs for D_{int} and D_{ext} respectively. In order to compute a pdf for total dose, D_{tot} , the degree of correlation between these two distributions must be considered. In practice, some correlation (positive or negative) will exist because of physiological characteristics, as both internal and external doses are taken to depend upon body mass, m . There will also be a strong positive correlation because internal dose depends on the concentrations of radionuclides in foodstuffs drawn from the utilisation area and these concentrations will depend, in part, on the concentrations in the underlying soils, which are the primary determinant of external exposure rates. It is proposed that perfect correlation between the internal and external dose estimates be assumed, recognising that this will result in a slight over-dispersion of the final distribution.

This perfect correlation is achieved in the methodology set out in Sections 2.1 and 2.2, by selecting sets of m, r and x for use in both the internal and external dose calculations because together these three quantities completely determine both internal and external exposures for an individual with the selected physiological characteristics occupying a resource area centred on x .

3. COMPLIANCE WITH THE CRITERION ON TRANSURANIC CONCENTRATIONS IN SOIL

In this case, the compliance criterion is that the total concentration of transuranics (in practice ^{239}Pu , ^{240}Pu and ^{241}Am) should not exceed 17 pCi g^{-1} (629 Bq kg^{-1}).

The main consideration here is the area over which concentrations may appropriately be averaged to compare with the criterion, since surface soil samples to a depth of 5cm are specified as part of the criterion. In the RRP, soil samples are composites from three locations within a few metres of each gamma survey point. Thus, they are characteristic of average soil concentrations on a spatial scale of a few metres and are taken on a rectangular grid of side 200m. Soil concentrations are likely to be heterogeneous on a variety of spatial scales, but the distribution of concentrations measured in the RRP will be more broadly distributed (over-disperse) than the average concentrations appropriate to spatial scales of more than $\sim 10\text{m}$. This is because the variations between the observed concentrations are due to both sub-grid scale and super-grid scale variations, so that spatial averaging at the grid scale tends to suppress sub-grid scale variations while leaving super-grid scale variations unaltered.

As with the in situ gamma measurements, it is possible to predict the spatial variation of soil concentrations, $C_{\text{TU}}(x)$, at any location x , using a smooth function that minimises the mean-squared prediction error given by the observations. It is the smoothed predictor that is used for comparison with the compliance criterion, since it eliminates small-scale and sampling variability, which is of little consequence in determining whether individuals are on average exposed to soil concentrations exceeding 17 pCi kg^{-1} .

It is also possible to define $T_{\text{TU}}(x)$ values using:

$$T_{TU}(x) = (\pi R^2)^{-1} \int C_{TU}(x-y) dy$$

where the integration is over a disc of radius R centred on x.

Values of $T_{TU}(x)$ may be used to investigate the average soil concentrations encountered over different resource utilisation areas. However, it is emphasised that $C_{TU}(x)$ and not $T_{TU}(x)$ should be used in the evaluation of compliance.

4. REFERENCE

1. ICRP Publication 56. Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1. Annals of the ICRP, 20(2), 1989.

APPENDIX A3

RADIOLOGICAL MONITORING AND ANALYSIS

RMI Nationwide Radiological Study

- (i) Summary Report on Radiological Monitoring Program (S. L. Simon and J. C. Graham)
Determination of External Exposure-Rates (S. L. Simon)
- (ii) METHODOLOGY (S. L. Simon, J. C. Graham and A. Borchert)
 - Minimum Detection Limits
 - Gamma Spectrometry Methodology
 - Error Analysis for Gamma Spectrometry
 - Methodology for Measurement of Plutonium in Soil
 - Error Propagation for Alpha Spectrometry Measurements
- (iii) Results of Measurement Intercomparison Between RMI Nationwide Radiological Study and Lawrence Livermore National Laboratory (J. C. Graham and S. L. Simon)
- (iv) RADIOLOGICAL SURVEY FINDINGS (S. L. Simon and J. C. Graham)
 - List of Island Names
 - Sampling Maps
 - Soil Profile Results
 - Tables of Radiological Measurement Data
 - Probability Distributions of Radioactivity Measurement Data for Local Foods
 - Small Grid Interpolation Maps
- (v) Geostatistical Analysis of Radionuclides on Rongelap Island (P. Diggle, L. Harper and J. Tawn, University of Lancaster)

SUMMARY REPORT ON RADIOLOGICAL MONITORING PROGRAM FOR RONGELAP RESETTLEMENT PROJECT

S. L. Simon and J. C. Graham

INTRODUCTION

The purpose of this chapter is to explain the objectives, design and methodology of the radiological monitoring activities as carried out in support of the Rongelap Resettlement Project (RRP). These methods were used in partial fulfillment of the overall objectives of the Scientific Work Plan of the Rongelap Resettlement Project (i.e., that plan submitted to the U.S. Congress on 19 September, 1991).

Review of Rongelap Resettlement Project Objectives:

The two main objectives of the overall Project were to determine the suitability of reinhabiting Rongelap Island and the southern islands of Rongelap Atoll based on two criteria which must be found to be in compliance before resettlement should take place: (1) projected doses to all members of the Rongelap community should not exceed 100 mrem/year above background, and (2) the concentration of transuranics in the soil (averaged over the top 5 cm) does not exceed the current EPA recommended screening level of $0.2 \mu\text{Ci}/\text{m}^2$. Both of these criteria were developed in order to ensure the safety of the population, should they decide to reinhabit Rongelap Island.

Other lesser objectives were also a part of the scientific investigations conducted by the RRP. These included the study of the microdistribution of plutonium in soil, urine and in bones of deceased and previous residents of Rongelap. Findings from these research initiatives are reported in other chapters.

Objectives of Radiological Monitoring Program

The objective of the radiological monitoring program was to collect environmental radiological data on Rongelap Island and the southern islands of Rongelap Atoll (see Appendix A3, Section (iv) for a map of the study area) which could be used: (1) to compare with data from other institutions, (2) to perform the radiological assessment as specified in the Memorandum of Understanding, (3) to provide advice and guidance about the potential risks in resettlement, (4) to provide advice regarding the need for remediation programs, and (5) to assist in determining appropriate recommendations for remediation if required. The sampling density was determined by several factors including the available funding for conducting the radiological measurements, availability of transportation to Rongelap and the availability of other services required for the

conduct of those trips. Statistical guidance was used to formulate the objectives where possible. In particular, the number of in-situ spectrometry measurements on Rongelap Island for ^{137}Cs was intended to ensure that the 95th percentile of the that distribution was not underestimated at a confidence level of 95%.

Measurements of ^{137}Cs , ^{241}Am and $^{239+240}\text{Pu}$ were planned and made as part of this study. Measurements of ^{90}Sr were not planned because of limitations of equipment, time and funding resources. Moreover, it was perceived that measurements of ^{90}Sr from LLNL could be used following the intercomparison of data of other radionuclides.

The Need to Compare Data From Other Studies

One objective of the program was to collect environmental radiological data and perform a comparison with samples measured by Lawrence Livermore National Laboratory (LLNL) or with data reported in the literature, e.g., in the 1978 Aerial Survey of the Northern Marshall Islands EG&G (1981). The usefulness of this exercise was to confirm a larger data set of information than could be accumulated by the RRP monitoring program. Considerable costs savings to all parties could be realized by confirming data, rather than by replicating it.

The data reported in EG&G (1981) were island-averaged terrestrial exposure-rate and soil concentration values and exposure-rate and soil concentration contour maps (of ^{137}Cs and ^{60}Co in soil) superimposed on aerial photographs of the islands. (see Figs. D-41, 42, and 43 of that report for data of Rongelap Island.)

Other data from Rongelap for possible comparison has been reported by Robison and Phillips (1989). However, a more relevant objective was satisfied by a split sample comparison program.

Results of comparing data from both of these sources is presented in this report [see Appendix A3, Section (iii)].

Summary of Methodologies Used in Radiological Survey

Consistent with the objectives of the radiological monitoring component of the Rongelap Resettlement Project, the following radiological measurements and sample collections were made.

(1) In-situ gamma spectrometry - High resolution gamma spectral measurements were recorded to quantify the local inventory of gamma photon emitting radionuclides in the soil on an area-averaged basis. This information was used to calculate above-ground exposure and dose-rates and areal inventory of gamma photon emitting radionuclides. Sampling plans are discussed in this document.

(2) Soil profile collection and laboratory gamma spectrometry - Soil profiles were collected for the purpose of determining the vertical concentration gradient of gamma photon emitting radionuclides in the soil by laboratory measurement. The main radionuclide of interest was

^{137}Cs , however, ^{241}Am and ^{60}Co were also measured where present. The profile measurement results were to determine relaxation lengths, a quantity useful in calibrating the in-situ gamma spectrometer. Findings are provided in this report in Appendix A3, Section (iv).

(3) Surface soil collection and laboratory alpha and gamma spectrometry- Surface soil samples (0 - 5 cm depth) were collected to determine compliance with the EPA screening value for transuranics in soil as outlined in the Memorandum of Understanding (see Appendix I, this report). Radiochemical extraction of plutonium, followed by alpha spectrometry was conducted to evaluate the surface soil concentration. Findings are provided in this report in Appendix A3, Section (iv).

(4) Sampling of locally grown foods and laboratory gamma spectrometry - Local foods were sampled as available and analyzed in the RMI radiological laboratory for gamma emitting radionuclide content. Findings are provided in this report in Appendix A3, Section (iv).

(6) Sampling of native vegetation and laboratory gamma spectrometry - Vegetation from plants other than those used for foods were sampled on a limited basis for laboratory analysis of ^{137}Cs . Findings are provided in this report in Appendix A3, Section (iv).

Equipment

The following equipment owned by the RMI Nationwide Radiological Study was made available in support of the activities of the radiological field survey of Rongelap.

- Two portable HPGe gamma spectrometers for in situ measurements - Canberra® coaxial high purity germanium (HPGe) 40% efficiency detectors with 7 liter liquid nitrogen dewars; portable, battery-operated, multi-channel analyzers (Canberra S-10+ with 4096 channels); data storage tape recorders, portable computer, tripods, water-resistant carrying cases, supply of liquid nitrogen.

- Two FIDLER detectors - Bicorn® FIDLER low-energy photon detectors optimized for detection of ^{241}Am : 2 mm thick NaI crystal optically coupled to 5" diameter photomultiplier tube, 0.010" thick aluminum window (95% transmission at 60 keV), ruggedized, with aluminum carrying handles, two Bicorn Micro-Analyst® integrating or instantaneous count-rate scalers with single channel analyzers (SCA), waterproof carrying cases.

- Two portable NaI counting systems - one 3" x 3" and one 1" x 1" probe, two Bicorn Micro-Analyst® integrating or instantaneous count-rate scalers with single channel analyzers, waterproof carrying cases.

- One portable pressurized ionization chamber - Reuter-Stokes® high pressurized argon ionization chamber and electrometer (0-100 mR/h) with LCD readout, memory for holding 500 data points, battery operated, tripod, water-resistant carrying cases.

- Two hand-held energy compensated Micro-Rem survey meters - Bicorn Micro-Rem® tissue-equivalent survey meters, organic scintillator, 0-20 μR , μrem , $\mu\text{Sv/hr}$ full scale, waterproof carrying cases.

- Two GPS (Global Positioning System) readout devices - Magellan Nav 1000 Plus® GPS devices, hand held, waterproof, LCD readout, provides longitude and latitude of location to ± 25 m absolute on earth's surface; used for documenting sampling and measurement locations.

Nonreusable field and sampling supplies, e.g., polyethylene sample bags, plastic containers for liquids, etc. were purchased as needed.

The following equipment owned by the RMI Nationwide Radiological Study was made available in support of the activities of the laboratory analysis of samples obtained in the field survey of Rongelap.

- Two extended low-energy HPGe gamma spectrometers - Canberra® coaxial high purity germanium (HPGe) 40% efficiency detectors with electrocool compressors (liquid helium recirculation) and computerized gamma spectrometry system.
- Two alpha spectrometry detectors (vacuum chambers, passively implanted planar silicon detectors (PIPS) and computerized alpha spectrometry system.
- Facilities for preparing soil for measurement (drying, crushing and sieving) and use of a complete radiochemistry laboratory for extraction of plutonium.

SAMPLING CONSIDERATIONS

The sampling plan for this study had three main considerations: site selection, number of samples (or measurements), and resource allocation. The most fundamental limitation to sampling was available resources, in particular, laboratory operating costs and time which could be spent in the field. The latter was a function of time in which the support vessel (provided by the U.S. Department of Energy) could provide logistics support for each field trip. A secondary limitation was the number of samples which could be processed in the RMI laboratory.

SITE SELECTION

Site selection for in-situ gamma spectrometry

The selection of gamma spectrometry measurement sites in the survey of Rongelap was different than that for most other island surveys conducted by the Nationwide Radiological Study. Typically, the most undisturbed sites available are sought as measurement sites and sampling density is about 1 per 0.2 km². The undisturbed locations which are sought generally best represent the original deposition at that location. On Rongelap Island, however, the objective differed and consequently, the sampling design differed. For the purposes of the Rongelap Resettlement Project, it was required to obtain data which could be used to predict the distribution of doses among a community of possible future inhabitants. Thus, it was required to

obtain environmental radiation data at a much higher sampling density. Furthermore, the spatial variation of present day exposure conditions was of more fundamental interest than attempting to determine the original deposition value.

Other standard criteria for site identification were applied. These include ensuring that all measurement locations were at least 30 m from the high tide line on both ocean and lagoon shores and at least 30 m from any manmade structures. In places where human habitation was evident, the measurement site selected was generally where there was least evidence of environmental disturbance.

Data sheets were filled out in the field for every measurement and for every sample obtained. These records are on file at the RMI Nationwide Radiological Study Laboratory.

Site selection for surface soil samples

Surface soil (0-5 cm mixed) was collected for radiological analysis of transuranics to determine if there are locations which exceed the allowed concentration defined by the EPA screening level. Each surface soil sample was a composite of three smaller subsamples taken in the immediate area (within 10 m) of the gamma spectral measurement. Three 15 x 15 cm areas were identified which appeared to be relatively undisturbed. All vegetation and litter was carefully removed from the surface of the three sampling sites. Using a sharp trowel, the soil was removed to a depth of 5 cm and placed in a marked bag. The extracted soil from each of the three sites was 1125 cm³. The composite sample weighed about 4500 g. Each composite sample was double bagged and stored in a waterproof bag on the ship for transportation back to the laboratory.

The choice of sampling sites for surface soil was carried out with two factors in mind: (1) to provide data on locations with environmental conditions (e.g., soil type, organic layer depth, etc.) representative of the majority of the land mass on an island, and (2) to coincide with the location of an in-situ gamma spectral measurement.¹

Site selection for soil profiles

A sampling site for the vertical distribution of soil radioactivity (i.e., for soil profiles) was normally selected with two factors in mind: (1) to provide data on locations with environmental conditions (e.g., soil type, organic layer depth, etc.) representative of the majority of the land mass on an island, and (2) to coincide with the location of a gamma spectral measurement for the purposes of detector calibration.

¹The second requirement had only indirect bearing on the evaluation of transuranic radioactivity. The matched location data was used to predict the amount of plutonium present in the soil by the relatively easy measurement of ²⁴¹Am by gamma spectrometry. The predicted value was used to estimate tracer spiking levels before plutonium radiochemical analysis was carried out.

In sampling the profiles, vegetation and litter was removed from the surface of the soil. A large hole, approximately 1 m by 0.5 m was excavated. One side of the hole was then carefully cleaned of loose soil which may have been pushed up or down by the digging and, therefore, would not represent the depth from which it was to be taken.

The soil profile was sampled in 5 cm increments to a depth of 30 cm, the first sample being composed of the top 5 cm of soil. About 2.5 liters of soil was put into prelabeled plastic bags. Each double bagged sample was stored in waterproof container on the ship for transportation back to the laboratory.

Fewer soil profiles than gamma measurements are obtained to prevent redundant effort. Generally the ratio of soil profiles to *in-situ* gamma measurements was 1:5.

Twelve profiles were collected from Rongelap Island on the survey trip in November 1991 as well as four from other islands. Thirteen more were collected in April of 1992 and five more in September of 1992. Further information concerning the number of samples obtained on each trip is provided in a set of tables at the end of this section.

A data sheet was filled out in the field for every profile. Additional data sheets are on file from the laboratory measurements.

Sampling of locally grown foods

Sampling of locally grown foods was carried out as part of the data collection and confirmation monitoring program. Locally grown foods sampled included coconut, Pandanus, breadfruit, banana, and arrowroot. It was not possible to devise a statistical sampling plan for fruits, rather fruit samples were obtained as could be located.

The only abundant fruit was coconut. The coconut samples were generally collected in areas of low disturbance and usually near a gamma spectral measurement location. The only requirement placed on tree selection is that the nuts were of drinking maturity. The coconut sample consisted of 5-10 nuts collected from the same tree. The nuts were drained and the sample was stored in a plastic container. The total volume collected from one tree was usually 1 to 2 liters. The mede (soft coconut meat) was collected from nuts after the milk was collected. It was carefully removed from the nuts with a spoon to prevent soil contamination. The mede was stored in plastic containers or ziplock bags.

A soil sample was also collected at the base of the sampled tree to provide data regarding the uptake ratio. The soil sample was from approximately 0-30 cm depth, and was collected equally from two holes.

As with all sample collected, a data sheet was filled out in the field and laboratory data sheets were maintained.

Sampling of native vegetation - study of traditional medicinal plants

Sampling of certain native vegetation species for radiological analysis was carried out to complement other measurements used in the assessment of potential exposure via ingestion. The plant species of particular interest were those used in traditional Marshallese medicine. The monitoring of these plants was a unique aspect of the overall radiological evaluation.

Findings are reported in data tables in Appendix A3, Section (iv) and are reported in more detail by Duffy (1994). Five species were sampled from a list of plants developed in consultation with an historian at the Alele Museum in Majuro. These plants are known to be ingested for medicinal purposes, thus, they are of interest from a radiological protection perspective. Some information on these species at Rongelap was reported by Donaldson (1959), however, in that case, the emphasis was not on evaluating the dose contribution from medicinal plant usage.

Sampling design was of limited use for these plants. Some species, *kino* in particular, were difficult to find. Thus, a limitation was in locating adequate plant specimens. The desired sample mass to be collected was approximately 4 liters of plant material. In addition, soil from the root zone of the plant was sampled.

The medicinal type plants which are reported here include:

<u>Scientific Name</u>	<u>Marshallese name</u>	<u>Plant part</u>
<u>Tournefortia argentea</u>	<i>kiden</i>	leaves
<u>Morinda citrifolia</u>	<i>nen</i>	fruit, flowers, leaves
<u>Scaevola taccada</u>	<i>kinnat</i>	leaves
<u>Triumfetta procumbens</u>	<i>at'at</i>	leaves
<u>Polypodium scolopendra</u>	<i>kino</i>	leaves

SAMPLING PLANS -STATISTICAL CONSIDERATIONS

Gamma Spectrometry

The sampling plan used for gamma spectral measurements and surface soil samples on Rongelap Island was systematic. A diagram of this sampling plan is shown in appendix A3, Section (iv). Systematic sampling was chosen to ensure a relatively complete and uniform coverage of the entire area of Rongelap island. In this sampling plan, the population for the gamma spectral measurements was defined to be the set of all independent (i.e., non-overlapping) circular areas of approximately 20 m radius². This is the approximate area which is viewed by the *in-situ* gamma spectrometer. Each of these units are approximately 1260 m². Since the total land

²This land area contains over 90% of the radioactive ¹³⁷Cs atoms whose gamma photons are detected by the spectrometer.

area of Rongelap Island plus the other islands in southern Rongelap Atoll is approximately 6.2 km², there are approximately 5200 independent samples. The majority of the possible sampling units are on Rongelap Island itself because it encompasses the greatest portion of the land area.

The contamination of Rongelap Island resulted from aerial deposition, thus, it is quite unlikely that any spatial periodicities of contamination should exist. The suspected presence of periodicities would be the main reason for not selecting a systematic sampling plan. Moreover, man-made disturbances on Rongelap Island from years of habitation would have diluted any such phenomena if they were to have existed.

As stated in the Republic of the Marshall Islands responses to the U.S. Congress, October 1991, a range of doses was to be predicted from the dose assessment. This was the intended assessment endpoint because there is a distribution of average intake-rates among the population and because there are variations in the amount of radioactivity present at various locations on the island. To enable these calculations to be made, a high degree of coverage of the island was attempted in the sampling plan.

The sampling plan attempted to specify the proportion of the range of sample values that would likely be contained in the sample, at a stated confidence level. Since the degree of environmental variability was not known *a priori*, nonparametric estimation methods were employed to estimate the required sample size.

Sampling density was also determined by the practical limitation of time available to work on Rongelap Island. This parameter was generally determined by mission requirements of the U.S. Department of Energy's environmental monitoring programs conducted through the Lawrence Livermore National Laboratory. In some cases, resource limitations (e.g., food, fresh water, fuel, etc.) of the ship supporting the mission had to be considered in planning the length of a field survey trip.

Related to the time allotment of the supporting vessel was the time required to obtain gamma spectral measurements on Rongelap Island. Significant time and effort was devoted to clear a path through the underbrush to reach each measurement location, setting up the spectrometer system, obtaining the spectral measurement (usually only a few minutes), down-loading the spectrum to a computer, packing up the equipment to prevent damage during movement and moving to a new location.

Although the RMI radiological study owned two portable gamma spectrometry systems, limitations in manpower usually dictated that only one system was in operation. Each system required a minimum of four persons. A number of tasks had to be completed by this team including: determining the next measurement location with compass and steel tape, cutting through the brush, moving the equipment (including weatherproofing gear, drinking water, etc.), operating the equipment, taking field notes and collecting the surface soil sample.

The overall sample size (sampling density) was determined from a combination of the resource limitation and statistical considerations. The basic question which the sampling design attempted to answer *a priori* of the survey missions was: how many samples (or measurements) were needed to

characterize the distribution of values such that the extremes (the high end in particular) would be well represented (i.e., not underestimated).

Rongelap Island was estimated from aerial photographs to be approximately 2.4 km² land area (aside from open beach). This area can be approximately divided into sixty 200 x 200 m units. We examined the potential of characterizing the island with 60 sixty measurements. The sampling design question was thus reformulated to be:

- What is the proportion of the full range of soil concentrations³ and localized exposure-rates³ that would be sampled by 60 measurements and what is the associated confidence level?

Non-parametric tolerance limits (two-sided) were utilized to evaluate this question. Conover (1980) shows that for sample size of n , the probability is $1-\alpha$ that the random interval from X_r to X_{n+1-m} inclusive contains a proportion 'q' or more of the population according to the estimation:

$$n \cong \frac{1}{4} x_{1-\alpha} \frac{1+q}{1-q} + \frac{1}{2} (r+m-1)$$
 where $x_{1-\alpha}$ is the $(1-\alpha)$ quantile of a chi-square random variable with $2(r+m)$ degrees of freedom and $r=m=1$ for a two-sided limit.

The use of tolerance limits assumes that the samples have been selected at random. Sampling was carried out, systematically with an arbitrary starting point. Further, the environment is believed to be a random field, i.e., without periodicities. Thus, random sampling was probably accomplished satisfactorily. In any case, the technique described above was used only for guidance.

We determined that sampling at least 93% of the range was acceptable to be sampled at a 90% confidence level. In this case:

$$n \cong \frac{1}{4} 7.779 \frac{1+0.93}{1-0.93} + \frac{1}{2} (1+1-1) = 60$$

The estimation of sample size also addressed an equally important question concerning the probability of determining the near maximum values on the island. A one-sided tolerance limit was also determined to address the question of what portion of the population may exceed the largest value sampled.

We determined that 59 samples would not underestimate the 95th percentile of the true range at 95% confidence:

$$n \cong \frac{1}{4} 5.991 \frac{1+0.95}{1-0.95} + \frac{1}{2} (1+1-1) = 59$$

³spatially averaged over approximately 20 m radius.

Both statements were used to confirm that 60 spectral measurements on Rongelap Island would adequately characterize the true distribution. Because the design called for a systematic grid (to ensure complete geographic coverage), the time required to complete the sampling was recognized to be significantly longer than acquiring random samples.

A systematic division of the island into sixty-three, 200 x 200 m cells is shown on the sampling map in the Appendix A3, Section (iv). The grid was design to run parallel to a N-S and E-W direction.

SAMPLES OBTAINED

In agreement with the sampling plan, in-situ gamma spectrometry measurements were made on a 200 x 200 m grid on Rongelap Island and all the southern island of Rongelap Atoll. A surface soil sample was collected at each site and profiles were obtained as shown on the island sampling map. Twenty-nine profiles were collected from the southern islands. Each profile contributes six increments; the total profile increments equalled 175.

Because the MOU agreement calls for an evaluation to determine if the total dose (above background) exceeds 100 mrem, it was determined important to try and ascertain if there might be areas of the island of any significant size with higher exposure-rates than we observed in the sampling of the 200 m grid. Following discussions with statistical consultant, Professor Peter Diggle of Lancaster University, it was decided to supplement the Rongelap Island database with a limited number of measurements taken at closer spacing. Four of the grid cells (i.e., the 200 m area blocks) were chosen for the purpose of acquiring additional measurement data and as representative of two different strata. Grid cell H2 and J3 were selected as "community land", i.e., land that is likely to have been significantly disturbed. Grid cells R27 and Q29 were selected to represent "wildland" or areas of the island that have likely been less disturbed. All four cells, were systematically divided into smaller grids of 25 measurement sites, 40 m apart. This added another 98 measurement points (two of the subsample locations were off the edge of the lagoon shore).

METHODS

Soil Sample Preparation

Procedures for soil sample processing for the particular needs of the RMI Nationwide Radiological Survey were a variation of guidelines presented in the U.S. DOE Environmental Measurements Laboratory Procedures Manual (EML 1992). Cesium-137 is the main radionuclide of interest in deep soils, though surface soils were also analyzed for transuranic radioactivity as well. Cesium-137 is known to accumulate on clay size particles of 2-4 μm or less (Dictionary of Geological Terms 1976; USDA 1989) and clay minerals (e.g., illite, kaolinite and

montmorillonite), whereas soil in the Marshall Islands consists mainly of coral and humic material. Particles in the size fractions comparable to fine sand and clay result from weathering of larger coral rocks mainly by wave action. Because the entire sample contributes to the above-ground exposure-rate, none of the sample e.g., large rocks, etc.⁴, was excluded from the soil sample preparation process.

Soil samples were dried by spreading the sample in aluminum trays with liners under 120V, 75W flood lights for up to 130 hours. The samples were dried to completion as determined by reaching an equilibrium weight irrespective of drying time. The maximum time to reach 99% of dryness for the samples in this study was 90 hours.

A mechanized shaker sieving device was used to separate soil samples into particle size fractions. In this method, tare weights for sieve trays #10 (>2 mm), #20 (0.85 mm - 2.0 mm), #40 (0.425 - 0.85 mm), #60 (0.25 mm - 0.425), #80 (0.18 mm - 0.25 mm) and the receiving pan (0 - 0.18 mm) were first recorded. Samples were sieved through these trays at a shaker setting which minimized dust production. The time required for sieving was determined by measuring the minimum length of time such that the weight of the sieve trays did not continue to change substantially. The greatest change in weight of the trays occurred in the first 5 minutes during sieving. After 5 minutes of sieving, less than 1% change of sample mass in any tray was evident over the next 45 minutes. A sieve time of at least 5 minutes was used for all samples.

As recommended in the EML guide, soil should be reduced to <1.3 mm (15 mesh equivalent)⁵ to ensure an homogeneous mixture. In our methodology, any sample fraction not passing through trays #10 (>2 mm) and #20 (0.85 mm - 2.0 mm) were subsequently ground in a ball mill overnight. Any fraction of the sample which still did not pass through tray #20 (0.85 mm - 2.0 mm) was crushed in a manually operated device.

After completion of sieving and crushing, soil was mixed to ensure uniformity and aliquots were removed for gamma spectrometry and radiochemical extraction for plutonium analysis.

Determination of exposure-rate from individual radionuclides:

A high pressurized argon ionization chamber (HPIC) with electrometer was used on occasion for direct measurements of exposure-rate ($\mu\text{R/hr}$). The final reported values of exposure-rate (see Data Tables, Appendix A3, Section (iv)) were derived from in-situ gamma spectrometric measurements. Details of the calculation steps to determine exposure-rate of individual radionuclides is described in the following section.

⁴See Sec. 2.4.4.1 of HASL-300

⁵See Sec. 2.4.4.2 of HASL-300

Monitoring for ^{241}Am

At many measurement locations, hand held low-energy photon detectors (FIDLER type) with single channel analyzers were used to obtain low-energy gamma measurements indicative of the presence of ^{241}Am . This measurement, however, is confounded with the Compton scattered component of the ^{137}Cs gamma rays and was determined as too difficult to interpret.

Final reported values of ^{241}Am were obtained from laboratory measurement of surface soil samples (0-5 cm). Americium concentration in surface soil samples was determined by laboratory gamma spectrometry of the 59.5 keV emission. Gamma spectrometry measurements were made in the laboratory of the Nationwide Radiological Study on two, hyperpure germanium (HPGe) detectors with low-energy sensitivity extended to less than 20 keV. Estimation of exposure-rate from ^{241}Am is discussed in the next section. Our reported values of soil concentration and exposure-rate from ^{241}Am are reported in data tables in Appendix A3, Section (iv).

Tansuranic analysis of surface soil samples

Laboratory measurement methodology for ^{241}Am is described above. Plutonium concentrations were determined from laboratory radiochemistry using a technique of microprecipitation onto neodymium fluoride substrate, followed by measurement of alpha emission using passively implanted planar silicon detectors (PIPS) in a computerized alpha spectrometry system. A complete description of the radiochemical extraction procedure is provided in Appendix A3, Section (ii).

To confirm the precision of the methods used in the RMI laboratory, the Nationwide Radiological Study laboratory conducted its own interlaboratory comparison with blind sample analysis conducted at four other participating laboratories including Lawrence Livermore National Laboratory, Colorado State University (Department of Radiological Health Sciences), National Radiation Laboratory of New Zealand and GSF Institut für Strahlenschutz (Germany). Results of comparing values measured in the RMI laboratory with intercomparison results for the measurement of ^{241}Am , $^{239,240}\text{Pu}$ (and ^{137}Cs) were well within acceptable limits. A report of the intercomparison results was furnished to all participating laboratories.

Estimating soil concentration and areal inventory:

The estimation of soil concentration and areal inventory can be accomplished by at least two methods: (1) laboratory measurement exclusively, or (2) in situ gamma spectrometry and supporting laboratory measurements. The second method was utilized in this study. In this method, *in-situ* gamma spectrometry measurements and laboratory measurements of soil profiles obtained from the entire Marshall Islands nation were correlated. From that data, calibration factors for determining areal inventory and exposure-rate were determined. Details of these methods are described in the next section.

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Rongelap Samples Collected by the RMI Nationwide Radiological Study
11-17 November 1991

Island	In-situ Gamma Measurement	Deep Soil Profile (0-30) cm	Coconut Meat / Milk / Soil	Medicinal Plants / Fruit	Surface Soil (0-5) cm
Rongelap	58	12	2	9	58
Likoteke	2	1	2	2	
Erabot	1		2	5	
Keroka		1	2	3	
Enekan im	1	1	2	6	
Batbiten					
Arbar	1	1	2	6	
Total =	63	16	12	31	58

Rongelap Samples Collected by the RMI Nationwide Radiological Study
24 April - 2 May 1992

Island	In-situ Gamma Measurement	Deep Soil Profile (0-30) cm	Coconut Meat / Milk / Soil	Medicinal Plants / Fruit	Surface Soil (0-5) cm
Rongelap	5		9	21	20
Bokjalto	2	1		1	2
Bokankokit	2				2
Likoteke	4	1	1	3	4
Eonbeje	3	1		1	3
Enealo	3	1	2	1	3
Looj	4	1		2	4
Bokantarinae	3	1			3
Eneatok	20	3	3	1	20
Erabot	2	1			2
Burok	6	1	2		6
Keroka	12	1			12
Enekan im	6			4	6
Batbiten					
Arbar	5	1			5
Total =	77	13	17	34	92

Rongelap Samples Collected by the RMI Nationwide Radiological Study
20 - 21 September 1992

Island	In-situ Gamma Measurement	Deep Soil Profile (0-30) cm	Coconut Meat / Milk / Soil	Medicinal Plants / Fruit	Surface Soil (0-5) cm
Rongelap	25	5	4	50	
Total =	25		5	4	50

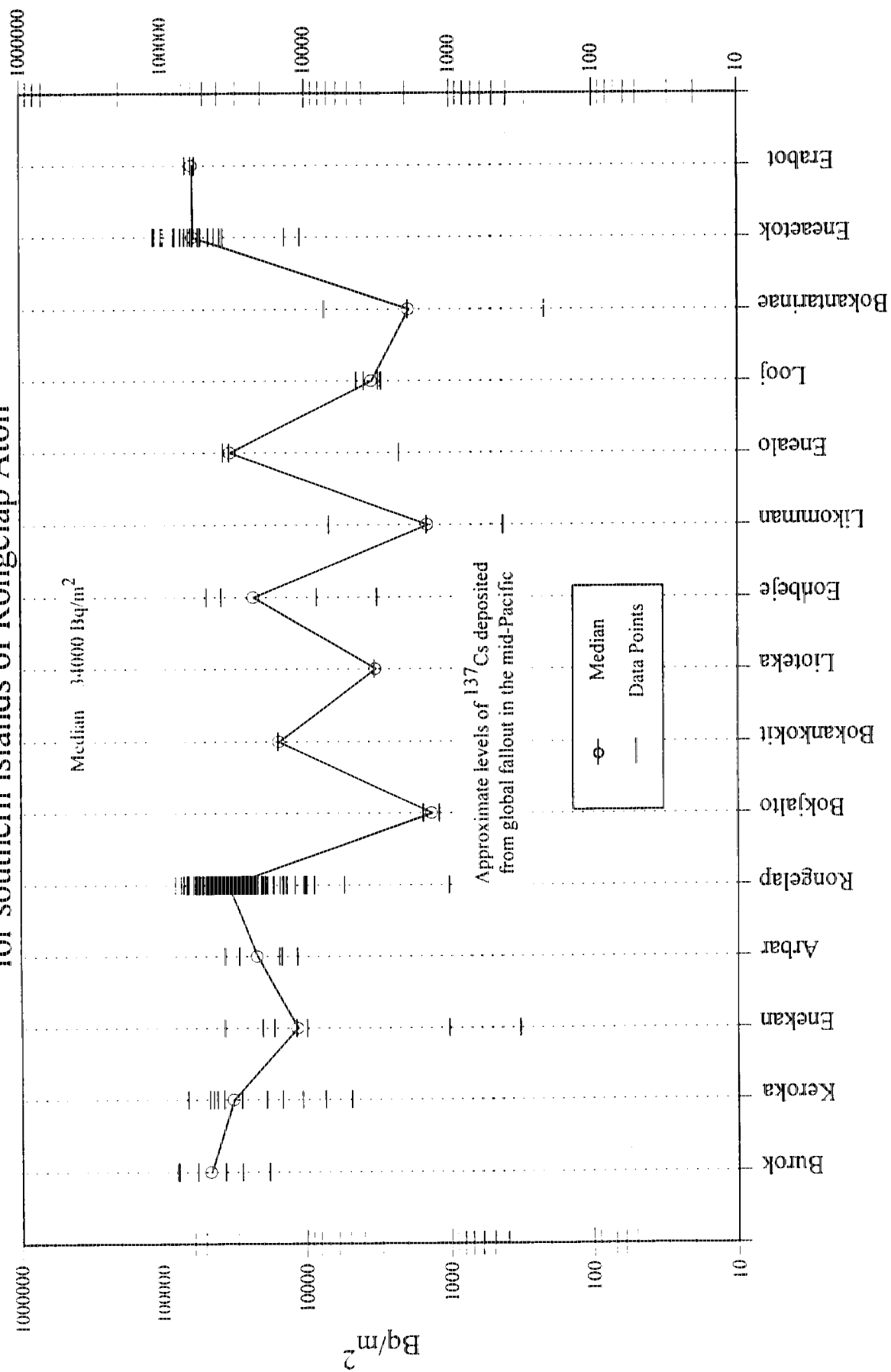
Rongelap Samples Collected by the RMI Nationwide Radiological Study
17 - 26 April 1993

Island	In-situ Gamma Measurement	Deep Soil Profile (0-30) cm	Coconut Meat / Milk / Soil	Medicinal Plants / Fruit	Surface Soil (0-5) cm
Rongelap	85				48

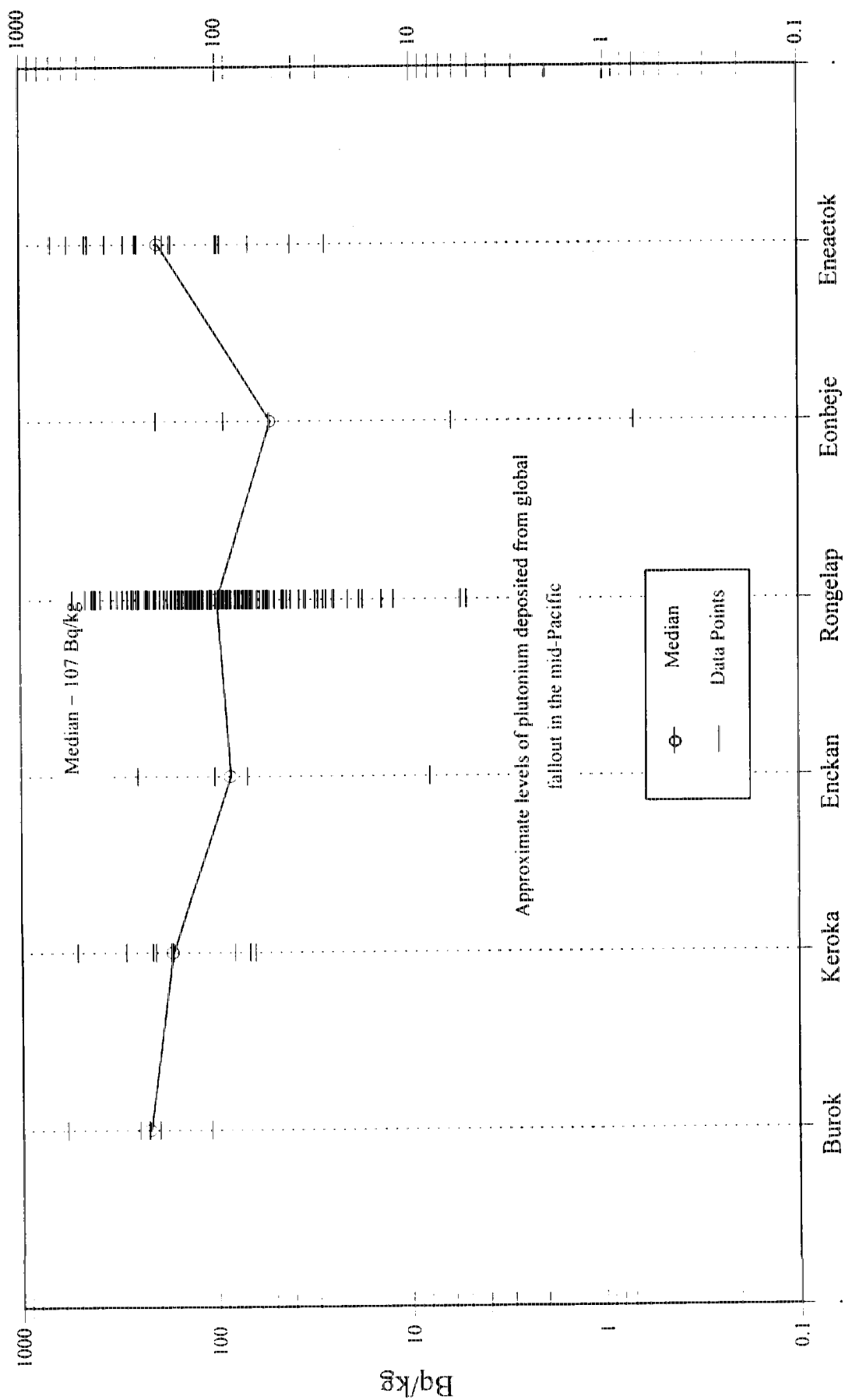
Summary Graphs of Measurements of Radionuclides by Island In Southern Rongelap Atoll

- (i) ^{137}Cs areal inventory (Bq/m^2 , 0-30 cm)
- (ii) $^{239}+^{240}\text{Pu}$ in surface soil (Bq/kg , 0-5 cm)
- (iii) ^{241}Am in surface soil (Bq/kg , 0-5 cm)
- (iv) ^{60}Co in surface soil (Bq/kg , 0-5 cm)

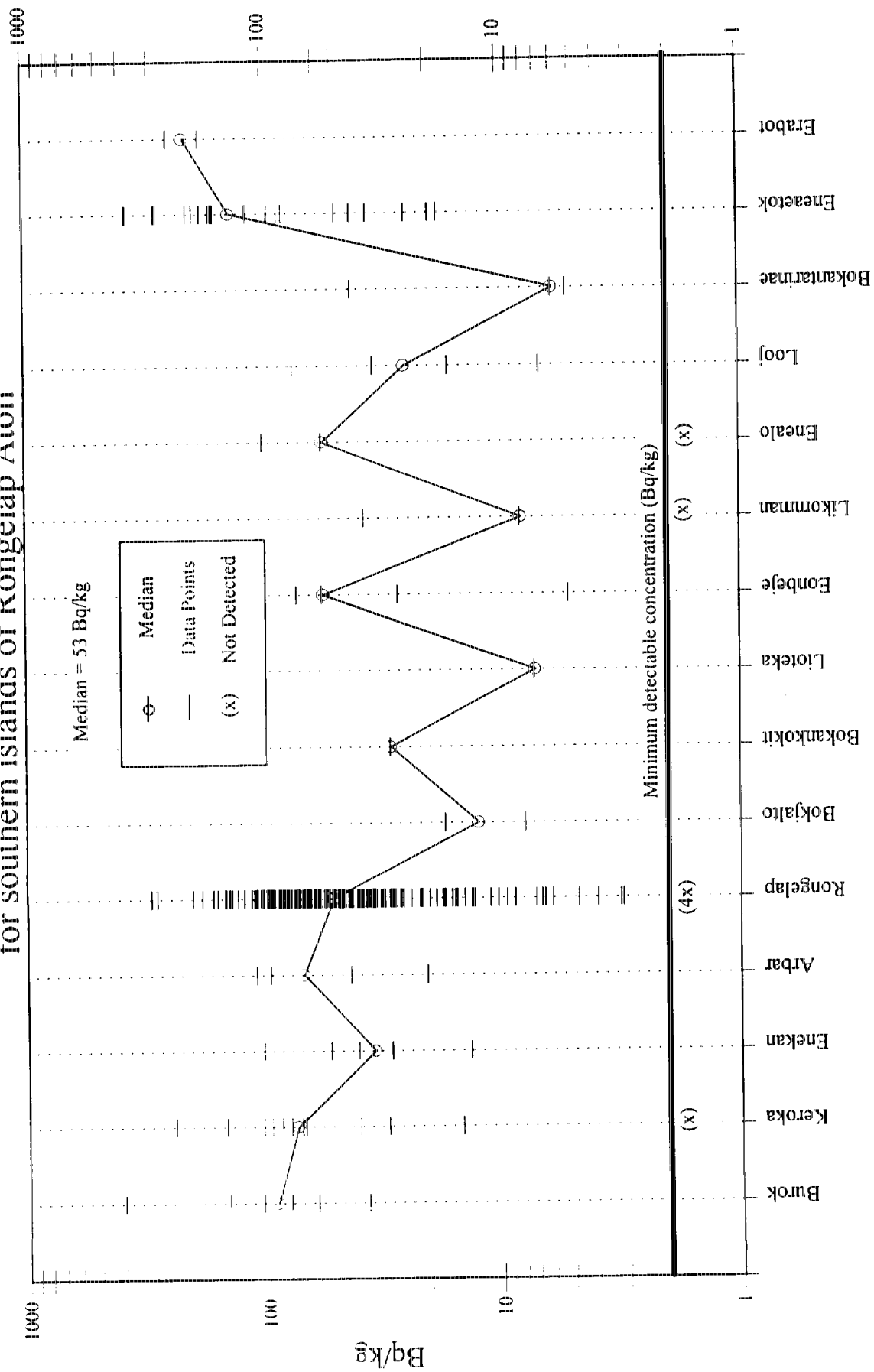
Areal inventory of ^{137}Cs (Bq/m^2) for southern islands of Rongelap Atoll



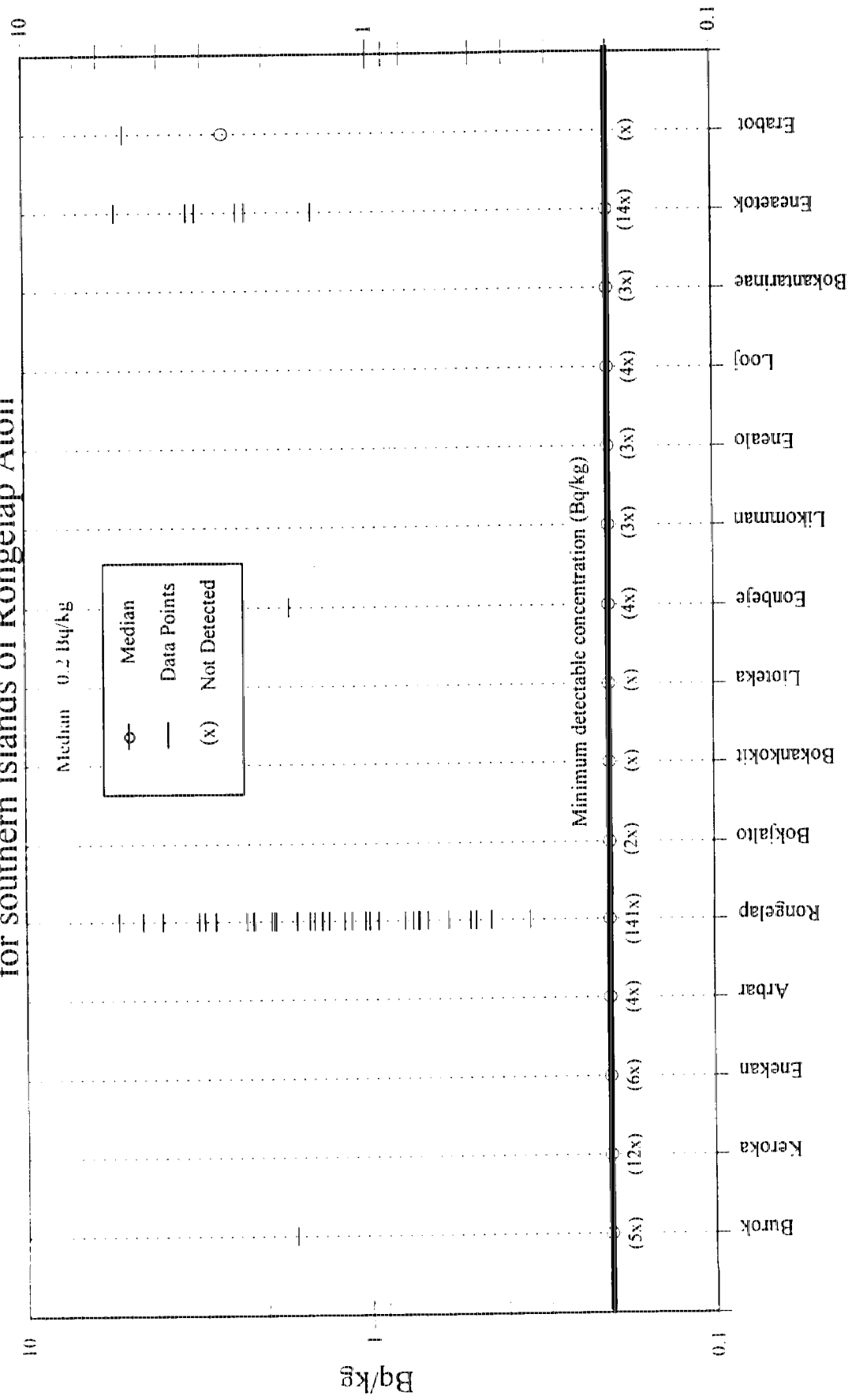
$^{239,240}\text{Pu}$ soil activity (Bq/kg) in 0-5 cm depth for southern islands of Rongelap Atoll



²⁴¹Am soil activity (Bq/kg) in 0-5 cm depth for southern islands of Rongelap Atoll



⁶⁰Co soil activity (Bq/kg) in 0-5 cm depth for southern islands of Rongelap Atoll



METHODOLOGY AND RESULTS OF DETERMINATION OF ANNUAL EXTERNAL DOSE-RATE

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RMI Nationwide Radiological Study

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Introduction

Exposure- and dose-rate resulting from external irradiation by ^{137}Cs in the soil was estimated in this assessment using data obtained from in-situ gamma spectrometric measurements and soil profiles. Exposure- and dose-rate from external irradiation due to ^{241}Am was inferred from data collected from laboratory analysis of surface soil samples and soil profiles.

Total outdoor exposure-rate (mR/y, i.e. cosmic + terrestrial + contamination) can be directly determined by instrument measurement, e.g., with a high-pressurized ion chamber, however, the exposure from natural radiation must first be subtracted to get the exposure from residual fallout radioactivity. Though that method is inherently simple, ion chamber measurements were not routinely made in the field survey of Rongelap. Rather, in-situ spectrometric measurements were used to determine exposure-rates. Although the latter method is more complex, it also allows for the determination of the areal soil inventory (Bq/m^2), a quantity useful for other purposes, e.g., predicting radionuclide accumulation in food crops.

External dose-rate to future inhabitants of Rongelap Island (i.e. mrem/y) was estimated by two different methods and compared. First, exposure-rate was calculated from ^{137}Cs using results from in-situ gamma spectrometric measurements and by applying the detector calibration methodology of Beck et al. (1972), supplemented with data from Helfer and Miller (1988). Exposure-rate was then converted to dose-rate. In a second method, dose-rate (Gy/y) was estimated using data from photon transport simulations by Jacob and Paretzke (1986) and an empirically determined relationship between in-situ count-rates and laboratory measured soil radioactivity from the Rongelap field survey.

In both methods, the exposure- and/or dose-rate was determined separately for each gamma-emitting radionuclide. The total exposure- and/or dose-rate was computed as the sum from the individual radionuclides.

Instrument and Sample Description

Three types of samples and/or measurements contributed to the information needed for estimation of external dose.

First, in-situ gamma spectrometry measurements were made on a systematic grid running N-S and E-W; measurement points were spaced at 200 m. Some allowance from the exact center point of each grid cell was made for natural or man-made obstacles, e.g., houses, coral boulders, etc. No measurement points were located close enough to the waters edge to necessitate count-rate corrections resulting from an island edge-effect. The first point (see map) AØ was located at the NE end of Rongelap Island. All other points were located relative to the first point by on-ground measurements made with a compass and steel measuring tape. Some degree of error exists in the location of measurement points. Although the amount of error in point locations is unknown, that error does not effect the exposure-rate calculations. The absolute location error probably did not increase geometrically with distance from the first point because compensating errors along the way likely occurred either in measuring distance and/or angle.

At other islands in Rongelap Atoll, in-situ measurements were made at the same spatial frequency (200 m apart). A surface soil sample (0 - 5 cm depth) was also obtained at each measurement site. The surface soil sample was actually a composite of three samples taken nearby (within 10 m) to the gamma measurement site. Finally, soil profiles were obtained from numerous measurement locations. Each profile consisted of six, 5 cm increments to a total depth of 30 cm.

Generally, the ratio of profiles to in-situ gamma measurements was 1 to 5. Each measurement and sampling site was determined by first locating the approximate grid point. Then, a visual assessment was made in an effort to find environmental cues which indicated a potential site with little historical disturbance relative to areas around it. Further information about sampling and measurement protocol is provided elsewhere in this report.

The in-situ gamma spectrometry measurements were made with hyperpure germanium detectors (HPGe) manufactured by Canberra™ Industries, Inc. Two detectors were used for all spectrometric measurements made by the NWRS during the field monitoring surveys. The characteristics of the HPGe detectors are noted in Table 1.

Table 1. Characteristics of HPGe detectors used for in-situ gamma spectrometry measurements. Both detectors closed-end coaxial type, nominal relative efficiency of 40% with attached 7-liter LN₂ dewar and enclosed preamplifier.

	Serial No.	Diameter (D)	Length(L)	L/D	Active Volume
Detector 1	5901937	61.5 mm	52 mm	0.846	144.5 cm ³
Detector 2	5901809	57.6 mm	62.5 mm	1.085	146.7 cm ³

Summary of measurement data available for exposure-rate calculations

¹³⁷Cesium

Rongelap Island was surveyed on a systematically spaced grid of 200 m between measurement points. There were 63 measurement sites (or grid cells) at this spacing on Rongelap Island. To study the variability within the grid cells, four cells (200 x 200 m each) were selected for more detailed study: H2, J3, R27 and Q29. Grid cells H2 and J3 were selected to represent the portion of the island that was most intensely utilized by the community, and hence, likely to have been disturbed to a greater degree than other parts of the island. Grid cells R27 and Q29 were selected to represent the portion of the island that was less likely to have been disturbed. Each of the four grid cells were subdivided into twenty-five, 40 x 40 m subcells and a gamma spectrometric measurement was made within each. This process added another 98 gamma measurements sites for Rongelap Island (two of the one hundred additional samples were off the island's edge).

The raw count-rate data for ¹³⁷Cs expressed as a Coefficient of Variation (σ/\bar{x}) was used to rank the cells by degree of variation H2 (CV=0.41) > Q29 (CV=0.36) > J3 (CV = 0.25) > R27 (CV = 0.20). Because the CVs for the community land areas were not distinct from the non-community land areas, there was no clear evidence that a simple and seemingly, intuitive distinction could be made about the degree of variation of count-rates in different locations of the island.

²⁴¹Americium

Laboratory measurements of surface soil samples obtained at the site of each in-situ gamma spectrometric measurement were used to assist in exposure-rate estimation. In many grid cells, the the counting times used for the in-situ spectrometric measurements were not long enough to insure high precision of the counting data for ²⁴¹Am. At some locations, americium was undetectable in the given counting time, however, it was detectable at all locations in laboratory measured soil samples.

⁶⁰Cobalt

Because of the relatively short half-life of ⁶⁰Co ($t_{1/2} = 5.2$ y), the cobalt inventory in the soil is low compared to that of ¹³⁷Cs. Thus, the counting times used for the in-situ spectrometric measurements were usually not long enough to insure high precision of the counting data for ⁶⁰Co. In many cases, the ⁶⁰Co inventory was below the minimum detectable concentration for the counting time used in the field survey.

A relationship between the in-situ count-rate of ¹³⁷Cs and ⁶⁰Co was determined using data from the entirety of Rongelap Atoll. This relationship was determined to be:

$$^{60}\text{Co (c/s)} = 0.00023 \times ^{137}\text{Cs (c/s)} \quad (r^2 = 0.92, n = 45) \quad (1)$$

The relationship shown above was used to estimate a count-rate for ^{60}Co at each of the grid locations for which there was no data.

Correlation of Soil Profile Results and In-Situ Gamma Spectrometry Measurements for ^{137}Cs

Individual increments of the soil profiles were prepared and analyzed for gamma emissions according to standard laboratory protocol. Plots of radioactivity concentration with depth are provided in Appendix A(3), Section (iv). The results of laboratory measurements of the soil profile resulted in an estimate of the concentration (e.g. ^{137}Cs or ^{241}Am Bq/kg) within each depth increment at each profile site. The relationships between in-situ data, surface soil sample data and profile data were examined and the results are discussed here.

The total areal concentration (Bq/m^2) of ^{137}Cs in each profile was estimated from measurements of the areal inventory in each profile increment by summing over the 6 depth increments. An average soil density of 1.0 g/cm^3 was assumed for these calculations:

$$\text{Profile areal inventory (total Bq/m}^2\text{)} = \sum_{i=1}^6 \left[\frac{\text{Bq}}{\text{kg}} \right]_i \times \frac{1 \text{ kg}}{1000 \text{ g}} \times \frac{1 \text{ g}}{\text{cm}^3} \times \frac{5\text{E}4 \text{ cm}^3}{\text{m}^2} \quad (2)$$

As expected, the in-situ measured count-rate was strongly correlated with the total areal inventory (Bq/m^2) of each soil profile. The relationship between Bq/m^2 and in-situ measured count-rates for ^{137}Cs (c/s) was examined. The following function was fit to the data:

$$^{137}\text{Cs (Bq/m}^2\text{)} = 4228.47 \times (\text{c/s})^{1.04}, \quad R^2 = 0.92 \quad (n=163) \quad (3)$$

Method 1: Determination of external exposure-rate and dose-rate by calibration of the in-situ gamma spectrometer

Theory

The methodology for determination of exposure-rate by calibration of the in-situ gamma spectrometer can be summarized as follows (Beck et al. 1972, ICRU 1994):

$$\frac{I}{N_f} = \left[\frac{N_o}{\phi} \frac{N_f}{N_o} \frac{O}{I} \right]^{-1} \quad (4)$$

where,

$\frac{N_o}{\phi}$ = ratio of the full-energy peak count-rate (c/s) due to a unit flux of gamma photons of energy E incident on the detector parallel to the axis of symmetry of the detector; this ratio is known as the "effective area" because units can be reduced to area, i.e., c/s per $\gamma/\text{cm}^2\text{-s} = \text{cm}^2$.

$\frac{N_f}{N_o}$ = the angular correction factor to account for the side response of the detector from gamma photons that are not parallel to the detector's axis of symmetry.

$\frac{\phi}{I}$ = the ratio of the flux at the detector due to a parallel beam of gamma photons from the nuclide of interest to the corresponding exposure-rate for that nuclide; this ratio is a function of the depth distribution of the radionuclide in the soil.

The above three terms were determined as follows.

(1) The term N_o/ϕ was determined for ^{137}Cs and ^{60}Co both by direct measurement as well as by prediction using the results of Helfer and Miller (1988).

The emission-rate from a radioactive point source placed over 1 m distance from the detector was measured to determine the counting efficiency for a parallel beam of photons. The "effective area" was determined to be 7.71 cm^2 and 4.80 cm^2 , respectively, for the 661.5 keV photon of ^{137}Cs and the 1173/1332 keV photon pair of ^{60}Co .

The "effective area" was also predicted by the regression model developed by Helfer and Miller (1988): $\ln(N/\phi) = a - b \ln E$, where a and b are regression constants as defined below and E is the photon energy in MeV, where

$$a = 2.689 + 0.4996 \ln \epsilon + 0.0969(\ln \epsilon)^2 \quad (5)$$

$$b = 1.315 - 0.02044 \epsilon + 0.00012 \epsilon^2, \text{ and} \quad (6)$$

ϵ = manufacturer's quoted detector efficiency, measured at 1332 keV relative to a $7.6 \times 7.6 \text{ cm}$ ($3 \times 3 \text{ inch}$) NaI(Tl) detector.

Using the above formulation, the "effective area" was estimated to be 7.69 cm^2 for ^{137}Cs , and 4.95 cm^2 for ^{60}Co , both very close to their measured values. The measured values of the "effective area" were used in subsequent calculations.

(2) The N_f/N_o term was determined by prediction for ^{137}Cs and ^{60}Co using the results of Helfer and Miller (1988). The angular response of HPGe detectors is mainly determined by the crystal dimensions, i.e., the ratio of the length to diameter. Values were found by interpolating the data

in Table 5 (i.e., Angular correction factor for downward facing detector and sources distribution of $\alpha/\rho \approx 0$) of Helfer and Miller (1988).

The approximate values of N_f/N_o for ^{137}Cs are 0.92 and 1.05 for detectors #1 and #2, respectively.

The approximate values of N_f/N_o for ^{60}Co are 0.93 and 1.03 for detectors #1 and #2, respectively.

(3) The term ϕ/I was determined from the calculations of Beck et al. (1972). The exposure-rate per increment count-rate for ^{137}Cs and ^{60}Co is weakly dependent on the vertical distribution of the radionuclide in the soil (i.e., α/ρ). For equal count-rates, radioactivity which is distributed deeply will have an additional Compton scatter component which adds to the exposure-rate as compared to radioactivity near the surface.

Application of method 1

Above ground exposure-rate is weakly dependent on the vertical profile of the radioactivity in the soil column. The rate of decline of radioactivity concentration with depth is the vertical distribution or "profile" and is described by a "relaxation length", measured in cm. The relaxation length is equal to $1/\alpha$ in the widely used exponential model:

$$S = S_o e^{-(\alpha/\rho)(\rho z)} \quad (7)$$

where S is the mass concentration at depth z , α is the inverse of the relaxation length and measured in $1/\text{cm}$, ρ is the soil density (g/cm^3), and z is the depth (cm).

The exponential model is useful because it describes the profile of aged fallout radioactivity in undisturbed soils. A plane source model is useful for radioactivity which has not significantly penetrated the soil, for radioactivity which has only a low energy emission or for fresh fallout which has no application here. For low energy emitters, the surface soil acts much like a plane source by effectively shielding above ground receptors from the lower soil depths.

The correct determination of α/ρ is important for several reasons. In particular, α/ρ is needed for determining the exposure-rate from in-situ gamma spectrometric measurements but is a more critical parameter for estimating the areal soil inventory (Bq/m^2). The determination of α/ρ , while theoretically simple, is sometimes difficult to determine in practice. In particular, fitting each set of six depth increments to a smooth mathematical model (e.g., $S_o e^{-\alpha z}$) is often problematic. Moreover, the uncertainty still exists as to whether any fitted depth profile is applicable to any other location, even if relatively close by.

The numerical value of α for each profile was determined by linear regression using the soil concentrations (Bq/kg) of the depth increments as measured in the laboratory. In routine calculations of fitting profiles to the exponential model, only the concentration values for the topmost three increments (i.e., 0-5 cm, 5-10 cm, 10-15 cm) were used. This eliminates any effect on the slope from deep layers which might deviate from the exponential model. Such layers

would effect the fit of the slope but would be too deep to significantly effect the observed above-ground count-rate. However, both the relaxation length from 0-15 and 0-30 cm are discussed here.

Soil density measurements were not routinely made as part of this study. However, the surface soil samples obtained at the site of each in-situ gamma measurement were of a specified area and depth and were thus used to empirically determine the surface soil density. Wet soil density values were computed from the dry weights and volumes of 179 soil samples of five cm depth each. Values ranged from a low of 0.2 g/cm³ to 1.3 g/cm³ with a mode value of 0.6 g/cm³ for the surface soil. Although this value appears relatively low, it is consistent with the porous nature of coral based soils and agrees with data from Rongelap Island published by Gessell and Walker (1992) from studies conducted in the late 1950's and early 1960's. The soil density will be somewhat greater in the environment due to the normal moisture content. Soil density values of 1.5 g/cm³ were reported by Tipton et al. (1981) from a study made at Enewetak Atoll on surface soils, however, these data do not appear applicable here.

Although the soil on the island likely increases in density with depth, it is only the uppermost layers that contributes most to the in-situ measured count rate and it is in these layers that the density is most likely the lowest because of higher organic matter content. An analysis of the profile inventories of 31 profiles from Rongelap Atoll shows that 70% of the ¹³⁷Cs activity resides in the topmost 10 cm. Thus, it is the topmost soil layers that are most important for exposure-rate determination.

The table below gives the calculated values of the relaxation length ($1/\alpha$, measured in cm) for ¹³⁷Cs determined from profiles from Rongelap Atoll (n=27, including 12 profiles from Rongelap Island). The relaxation length was calculated both for the depths of 0-15 cm and 0-30 cm depth.

Relaxation length summary statistics from Rongelap profiles	0-15 cm depth (cm)	0-30 cm depth (cm)
Minimum	3.2	4.9
Maximum	115.5	507.9
Points	27	27
Mean	11.6	26.9
Median	6.2	7.3
Std Deviation	21.6	96.2
Standard Error of the mean	4.2	18.5

In this method, an estimated value of α/p is needed for each in-situ gamma spectrometric measurement so that exposure-rate and/or the soil inventory can be determined. The data above shows the median relaxation length is between 6.2 to 7.3 cm.

Using a larger data set of profiles from the Nationwide Radiological Study, median values of the relaxation length were determined: 7.3 cm for 0-15 cm depth (n=108), and 8.7 cm for 0-30 cm depth (n=81). The coefficient of determination (R^2) for all these profiles was >0.90. Depending on the value of soil density assumed for the top layers of the soil, a range of α/ρ values can be determined as shown below.

median value of relaxation length (cm) from RMI profiles (see text above)	α (1/cm)	α/ρ assuming $\rho=1 \text{ g/cm}^3$ (cm^2/g)	α/ρ assuming $\rho=0.6 \text{ g/cm}^3$ (cm^2/g)
7.3	0.137	0.137	0.23
8.7	0.115	0.115	-- (see footnote a)

^a density of 0.6 g/cm³ for the depth range of 0-30 cm is considered unlikely

An estimate of the value of α is also needed for ⁶⁰Co. Five profiles in which there was sufficient ⁶⁰Co to determine an estimate of the profile slope showed that the cobalt had penetrated more deeply than ¹³⁷Cs. An average value of 0.048 cm⁻¹ was determined from the five profiles. Using a range of soil density from 0.6 to 1.0 g/cm³, α/ρ for ⁶⁰Co was estimated between 0.048 and 0.08 cm²/g.

Theoretical conversion factors for in-situ measured count-rates to exposure-rates

The factors for conversion of count-rate to exposure-rate were determined by the method outlined in Beck (1972). Taking into account the slightly different geometry of the two detectors resulted in two different sets of conversion factors for ¹³⁷Cs and for ⁶⁰Co.

¹³⁷Cs Figure 1 shows the fitted conversion factors ($\mu\text{R/hr}$ per ¹³⁷Cs c/s in full-energy peak) as a function of α/ρ . The two sets of data are specific for the efficiency and geometry of the detectors described in Table 1. For simplicity, however, it is justifiable to use a single average conversion factor:

$$\mu\text{R/hr per c/s} = 0.249 (\alpha/\rho)^{-0.122} \quad (8)$$

²⁴¹Am Exposure-rates from ²⁴¹Am were estimated using the results of laboratory measurements of the concentration in surface soil samples. The laboratory determined mass concentrations were converted to areal concentration using a surface soil density value of 0.6 g/cm³ for the 0-5 cm layer. The areal concentration value was used to predict exposure-rate using the conversion factor from Beck (1980) for an infinite plane source:

$$\mu\text{R/hr per Bq/m}^2 = 9.05\text{E-}6 \quad (9)$$

There is, of course, an implicit assumption in this calculation that the soil sample is representative of the grid cell.

⁶⁰Co Figure 2 shows the fitted conversion factors ($\mu\text{R/hr}$ per ⁶⁰Co c/s in full-energy peak) as a function of α/ρ . For simplicity, however, it is justifiable to use a single average conversion factor:

$$\mu\text{R/hr per c/s} = 1.23 \times (\alpha/\rho)^{-0.1006} \quad (10)$$

Method 2: Determination of external dose from in-situ spectrometry measurements using kerma factors

Theory

This method for determination of external dose-rate (e.g., mrem/y) from radioactivity in the soil uses the theoretical development of Jacob and Paretzke (1986) and our empirically derived relationship between Bq/m² in soil profiles and the *in-situ* count-rate.

Jacob and Paretzke (1986) used Monte-Carlo calculations to determine the spectral energy fluence at 1 m above the air/ground interface from point isotropic gamma-ray sources in the soil. The results of their calculations were a set of kerma factors of Gy/y per $\gamma/\text{s} \cdot \text{cm}^{-2}$ as a function of energy and source depth.

We fit the kerma-rate factors of Jacob and Paretzke of energies of interest (e.g., 662 keV for ¹³⁷Cs) to depth-dependent functions for the purpose of interpolating to depths not reported by them. Functions for the kerma-rate factors ($K = \text{Gy/y per } \gamma/\text{s} \cdot \text{cm}^{-2}$) for infinite, homogeneous isotropic plane sources in the ground for ¹³⁷Cs and ²⁴¹Am were determined to be:

$$K_i \text{ (for } ^{137}\text{Cs)} = 1.26\text{E-4} \times \exp(-0.174 \times d_i) + 1.06\text{E-4} \times \exp(-2.349 \times d_i) + 1.5\text{E-6} \quad (11)$$

$$R = 0.999$$

$$K_i \text{ (for } ^{241}\text{Am)} = 1.58\text{E-5} \times \exp(-0.439 \times d_i) + 8.92\text{E-6} \times \exp(-3.716 \times d_i) + 8.9\text{E-9} \quad (12)$$

where d_i = midpoint depth (cm) of increment i .

The function for the kerma factor for ²⁴¹Am was actually determined by interpolation of the fitted coefficients for the energies of 40, 50 and 100 keV. This is the reason that a correlation is not given. However, the fitting for the energies of 40, 50, and 100 keV was characterized by R values of 1.0, 1.0 and 0.9999, respectively. Therefore, it is expected that the interpolated function for ²⁴¹Am is quite close to its proper value.

Application of method 2

The above-ground dose-rate to air at the location of each soil profile was determined by the product of the K factor from the functions above, the total areal activity of each profile, and the gamma-branching ratio:

$$\text{Gy/y for profile increment } i \text{ } (^{137}\text{Cs}) = K_i \left(\frac{\text{Gy/y}}{\gamma/\text{s} \cdot \text{cm}^{-2}} \right) \times \frac{\text{Bq}}{\text{m}^2} \times \frac{1 \text{ m}^2}{10^4 \text{ cm}^2} \times \frac{0.85 \gamma/\text{s}}{\text{Bq}} \quad (13)$$

where the value of Bq/m² is determined from laboratory measurements (see equation 2).

$$\text{Gy/y for profile increment } i \text{ } (^{241}\text{Am}) = K_i \left(\frac{\text{Gy/y}}{\gamma/\text{s} \cdot \text{cm}^{-2}} \right) \times \frac{\text{Bq}}{\text{m}^2} \times \frac{1 \text{ m}^2}{10^4 \text{ cm}^2} \times \frac{0.36 \gamma/\text{s}}{\text{Bq}} \quad (14)$$

where the value of Bq/m² is determined from laboratory measurements (see equation 2).

Because the concentrations in the increments of the soil profiles were average concentrations, the K factors should be determined at a depth equal to the increment midpoints (i.e. 2.5 cm, 7.5 cm, 12.5 cm, 17.5 cm, 22.5 cm, and 27.5 cm).

Soil density must also be considered. The kerma factors calculated by Jacob and Paretzke, were for a soil of density 1.6 g/cm³. Because the soil is typically less dense in the Marshall Islands (~1.0 g/cm³), the above-ground exposure-rate will be slightly higher per unit of radioactivity in the soil. Thus, kerma values for the lower average soil density in the Marshall Islands were determined by multiplying the increment midpoint depth by the ratios of the densities. Thus, the value of depth d'_i used in the kerma equations was:

$$d'_i = d_i \left[\frac{1.0 \text{ g cm}^{-3}}{1.6 \text{ g cm}^{-3}} \right] \quad (15)$$

The above-ground dose-rate (to air) was then determined by summing the calculated kerma values from each of the six separate profile increments:

$$\text{Gy/y from } ^{137}\text{Cs (from total profile)} = \sum_{i=1}^6 \left[\frac{\text{Gy}}{\text{y}} \right]_i \quad (16)$$

$$\text{Gy/y from } ^{241}\text{Am (from total profile)} = \sum_{i=1}^6 \left[\frac{\text{Gy}}{\text{y}} \right]_i \quad (17)$$

Calculation of External Whole Body Effective Dose Equivalent

Conversion coefficients between exposure in free air from photons and whole body effective dose equivalent are found in ICRP (1987), Table 3a for a variety of exposure geometries. The conversion coefficients are given in that reference as a function of energy. These coefficients refer to isotropic irradiation of an anthropomorphic phantom at a point in free air 1 m above the ground. The conversion coefficients for ^{241}Am , ^{137}Cs and ^{60}Co are approximately $0.59 \times 10^{-2} \text{ Sv/R}$, $0.613 \times 10^{-2} \text{ Sv/R}$ and $0.65 \times 10^{-2} \text{ Sv/R}$, respectively.

These factors effectively account for body shielding and are appropriate for adult body sizes. Factors appropriate for children's body sizes will be greater.

Because these factors convert from exposure (i.e., R), they are easily used with the exposure-rates determined in the method by Beck. Using these factors with the dose-rates calculated by the method of Jacob and Paretzke require an additional step. Both conversions are shown below.

Method 1: Theoretical Calibration of In-Situ Detector (Beck, 1972):

^{137}Cs -Cesium

From equation (8): $\mu\text{R/hr per c/s} = 0.249 (\alpha/p)^{-0.122}$

^{137}Cs Whole Body Effective Dose Equivalent (EDE, mrem/y) =

$$0.249 (\alpha/p)^{-0.122} \frac{\mu\text{R/hr}}{\text{c/s}} \frac{24 \text{ hr}}{\text{d}} \frac{365 \text{ d}}{\text{y}} \frac{1 \text{ mR}}{1000 \mu\text{R}} \frac{0.61\text{E-2 mSv}}{\text{mR}} \frac{100 \text{ mrem}}{\text{mSv}}$$

$$= 1.33 (\alpha/p)^{-0.122} \frac{\text{mrem/y}}{\text{c/s}}$$

^{241}Am -Americium

From equation (9): $\mu\text{R/hr per Bq/m}^2 = 9.05\text{E-6}$

^{241}Am Whole Body Effective Dose Equivalent (EDE, mrem/y) =

$$9.05\text{E-6} \frac{\mu\text{R/hr}}{\text{Bq/m}^2} \frac{24 \text{ hr}}{\text{d}} \frac{365 \text{ d}}{\text{y}} \frac{1 \text{ mR}}{1000 \mu\text{R}} \frac{0.59 \text{ E-2 mSv}}{\text{mR}} \frac{100 \text{ mrem}}{\text{mSv}} \quad (18)$$

$$= 4.69\text{E-05} \frac{\text{mrem/y}}{\text{Bq/m}^2}$$

Method 2: Theoretical Calculation of Kerma (Jacob and Paretzke) and Empirical Calibration of Detector:

¹³⁷Cesium

To determine exposure-rate by this method, equations 13, 15 and 16 were used to determine Gy/y at the location of each soil profile. The conversion of units to mrem/y¹ is shown below. The exposure-rate (mrem/y) was calculated at each profile location.

¹³⁷Cs Whole Body Effective Dose Equivalent (EDE, mrem/y) =

$$\frac{\text{Gy } (^{137}\text{Cs})}{\text{y}} \times \frac{\text{R}}{0.00876 \text{ Gy}} \times \frac{0.61\text{E-2 Sv}}{\text{R}} \times \frac{100 \text{ rem}}{\text{Sv}} \times \frac{10^3 \text{ mrem}}{\text{rem}} \quad (19)$$

A relationship was then developed between the exposure-rate from ¹³⁷Cs in soil profiles (as determined by the kerma method) and the *in-situ* measured count-rate. This relationship allowed us to determine the exposure-rate at locations where only an in-situ count was obtained. The equation we fit was:

$$\text{mrem/y } (^{137}\text{Cs}) = 1.59 \times (\text{c/s})^{1.05}, \quad R^2 = 0.93 \quad (\text{n}=163) \quad (20)$$

where count-rate (c/s) is obtained from an in-situ measurement.

²⁴¹Americium

To determine exposure-rate by this method, equations 14, 15, and 17 were used to determine Gy/y at the location of each soil profile. The conversion of units to mrem/y¹ is shown below. The exposure-rate (mrem/y) was calculated at each profile location.

²⁴¹Am Whole Body Effective Dose Equivalent (EDE, mrem/y) =

$$\frac{\text{Gy } (^{241}\text{Am})}{\text{y}} \times \frac{\text{R}}{0.00876 \text{ Gy}} \times \frac{0.59\text{E-2 Sv}}{\text{R}} \times \frac{100 \text{ rem}}{\text{Sv}} \times \frac{10^3 \text{ mrem}}{\text{rem}} \quad (21)$$

$$\text{mrem/y } (^{241}\text{Am}) = 1.28\text{E-03} \times (\text{Bq/kg})^{0.98}, \quad R^2 = 0.97 \quad (\text{n}=96) \quad (22)$$

where Bq/kg is the concentration of ²⁴¹Am in a surface soil sample (0 - 5 cm depth).

¹mrem/y were the units used to determine compliance in the Memorandum of Understanding.

The final step for either Method 1 or 2 is to determine the total (^{137}Cs + ^{241}Am) effective dose equivalent-rate by summing the contributions from the individual radionuclides.

$$\text{total EDE (mrem/y)} = \text{EDE } (^{137}\text{Cs}) + \text{EDE } (^{241}\text{Am}) \quad (23)$$

Comparison of Two Dosimetry Methods

$^{137}\text{-Cesium}$

The method of Beck (1972) uses the concept of relaxation length to theoretically determine the above ground exposure-rate. At an *in-situ* count rate of 7 c/s (representative of the data from Rongelap Island), the exposure-rate is estimated to be 11.6 mrem/year.

The second method uses the kerma calculations of Jacob and Paretzke (1986) and an empirical calibration of *in-situ* count rate to areal inventory (Bq/m^2) in the soil. At an *in-situ* count rate of 7 c/s (representative of the data from Rongelap Island), the exposure-rate is estimated to be 12.0 mrem/year.

$^{241}\text{-Americium}$

Using the method of Beck (1972) and a surface soil concentration representative of Rongelap Island of 70 Bq/kg (approximately equal to 2100 Bq/m^2), the exposure-rate was estimated to be 0.099 mrem/year.

The second method uses the kerma calculations of Jacob and Paretzke (1986) and an empirical calibration of soil concentration (Bq/kg) to exposure-rate. At a surface soil concentration of 70 Bq/kg (representative of the data from Rongelap Island), the exposure-rate was estimated to be 0.080 mrem/year.

The agreement between the two methods was found to be, on the average, very close.

General Findings

Method 2 was used for routine calculations in the dose assessment reported in Appendix A5, Section (i).

External exposure-rate from ^{137}Cs on Rongelap Island was found to have a median value of approximately 11.3 mrem/y. The variation of exposure-rate measured on the 200 m grid and the 4 small grids are shown below. The coefficient of variation (σ/\bar{x}) of the 200 m grid data was about 44%.

External exposure-rate from ^{241}Am on Rongelap Island had a median value of approximately 0.07 mrem/y. The variation of exposure-rate measured on the 200 m grid and the 4 small grids

are shown below. The contribution to external exposure-rate from ^{241}Am is generally less than 1% of that from ^{137}Cs .

^{137}Cs external-dose (mrem/y)	200 m grid	H2 grid	J3 grid	R27 grid	Q29 grid
Minimum	0.35	3.42	7.77	9.20	6.64
Maximum	24.90	18.24	19.85	23.38	25.95
Points	63	23	25	25	25
Mean	11.41	10.53	11.84	16.85	14.43
Median	11.26	10.88	10.78	16.95	12.59
Std Deviation	5.03	2.99	3.15	3.47	5.41
Std Error	0.63	0.62	0.63	0.69	1.08

^{241}Am external-dose (mrem/y)	200 m grid	H2	J3	R27	Q29
Minimum	0.001	0.006	0.002	0.023	0.008
Maximum	0.226	0.318	0.112	0.336	0.138
Points	64	24	26	26	25
Mean	0.079	0.073	0.056	0.098	0.055
Median	0.074	0.062	0.057	0.087	0.047
Std Deviation	0.051	0.061	0.031	0.059	0.027
Std Error	0.006	0.012	0.006	0.012	0.005

Consideration of Spatial Variations

The external dose received by any individual depends on, aside from body size and the degree of shielding provided by houses, the amount of time spent on different parts of the island. Some locations, due to lower soil ^{137}Cs inventories, have lower associated external dose-rates.

Because it is impossible to predict the future behavior of any individual, it is not possible to predict the dose that will be received by individuals. However, it is possible to determine a distribution of dose-rates which will likely be received by different, but unidentified, members of the community.

The distribution of dose-rates in this analysis explicitly depends on the distribution of cesium inventories on the island. Thus, the distribution of annual exposure-rates in the grid cells is used here to estimate a distribution of annual exposures that would be received by a population which is equally distributed among all of the grid cells. However, the annual dose for persons who travels among the grid cells will be a time-weighted value of the dose-rates in the cells in which they move among.

Each grid cell is $4E4 \text{ m}^2$ in area and thus, is of a reasonable size for the purpose of collecting food. However, to the degree that each individual travels over the island and spends significant amounts of time in different sections of the island, their annual external dose will be determined by the weighting factors (i.e., fractions of the total time) describing the amount of time spent on different parts of the island:

$$\text{Annual average exposure-rate} = \sum_{i=1}^n w_i X_i \quad (24)$$

where,

w_i = fraction of the year spent at each location 'i', and

X_i = annual exposure-rate at each location 'i',

Each measured count-rate which is used to predict exposure and dose can be assumed to represent the average of the population of values within each 200 m grid, or it can be assumed as an estimate at a small point in space which varies from location to location, even within a single grid cell. These different assumptions have received considerable discussion and it is acknowledged here that there exist alternate methods for determining a distribution of meaningful exposure-rates for the community, particularly when it is assumed that residents will move about, but that we have no knowledge of the expected patterns of movement. Spatial averaging, in general, will produce annual doses less than the high end values on the distribution.

A separate section (Appendix A(3), Section 5) gives the results of using the set of in-situ measured count-rates to develop and calibrate a geostatistical model describing a smoothly varying exposure-rate "surface". The geostatistical model is used mainly for the purpose of predicting the count-rate at locations in between the measurement sites. The predicted values are then spatially averaged over a variety of radii which may describe various degrees of movement for members of the population. These spatially averaged values can be used to predict a distribution of annual dose-rates for various assumptions concerning community mobility.

Consideration of Shielding by Buildings

Consideration should be given to the effectiveness of Marshallese houses in shielding against external exposure. Most houses are constructed of plywood and many have a layer of crushed coral around the homes. Assuming that the coral layer is taken from the shore and is radiologically clean, the combination of the plywood house and coral layer will lead to a reduction in the exposure-rate in air. In this assessment, the reduction is assumed to equal 50%. The degree of effect of home shielding in mitigating the external dose for any individual, depends on the time spent there. Thus, the annual dose can be determined by a formulation such as the following

$$\text{External Annual Dose-Rate} = (\dot{X}_{\text{out}} \times [1 - t_{\text{indoors}}]) + (\dot{X}_{\text{out}} \times SF \times t_{\text{indoors}}) \quad (25)$$

where,

\dot{X}_{out} = average dose equivalent-rate (mrem/y) outside of the house and away from crushed coral layer,

SF = shielding effectiveness of houses (e.g., 50%), and

$t_{indoors}$ = proportion of total time spent indoors.

In the dose calculations provided in Appendix A5 by Simon, it is assumed that 9 hours per day are spent indoors. The remainder of the day is spent out-of-doors. Other assumptions can be easily input to modify the calculated annual external exposure.

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Figure 1 $\mu\text{R/hr per c/s for }^{137}\text{Cs}$
Method 1 (Beck 1972)

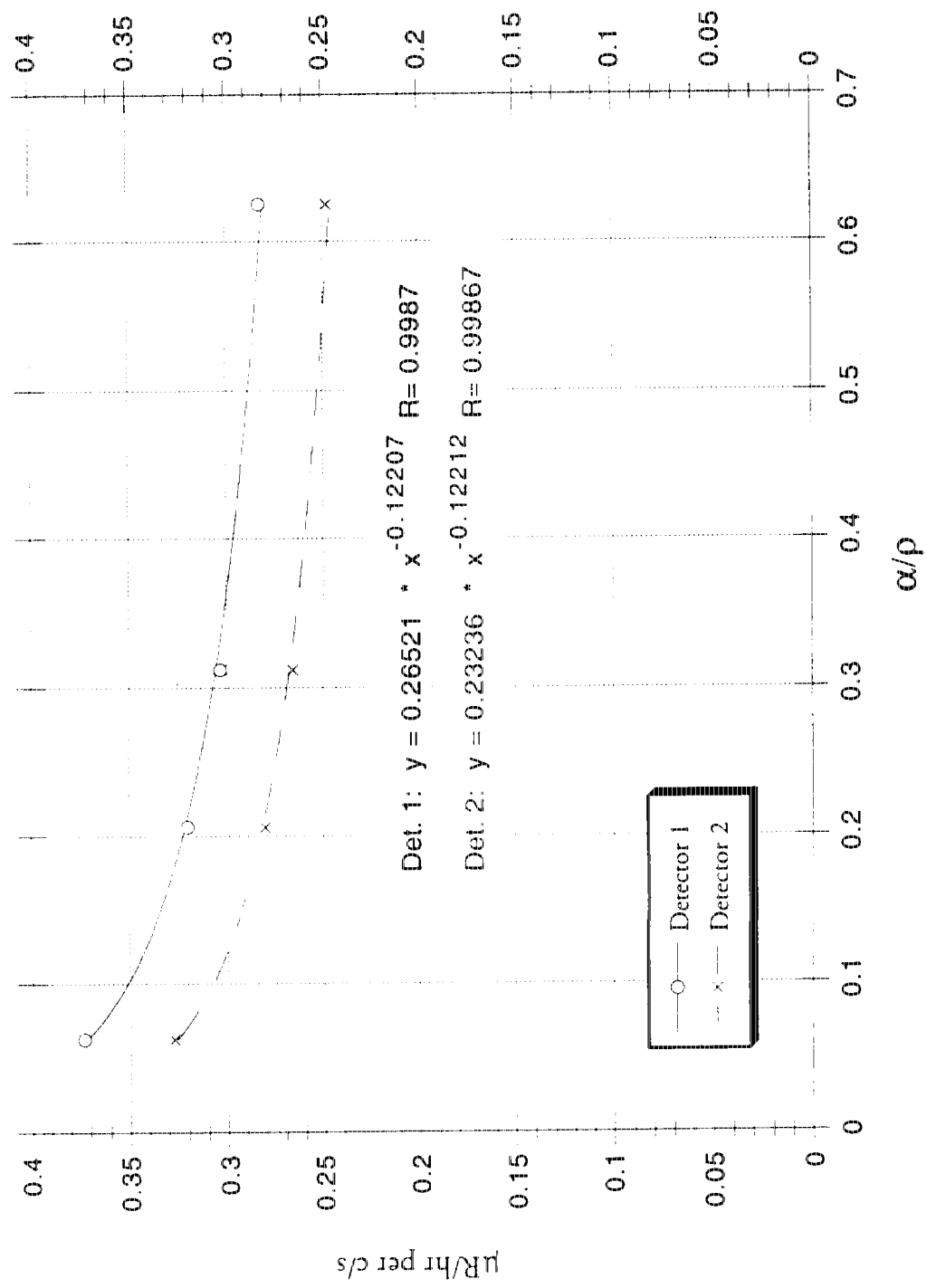
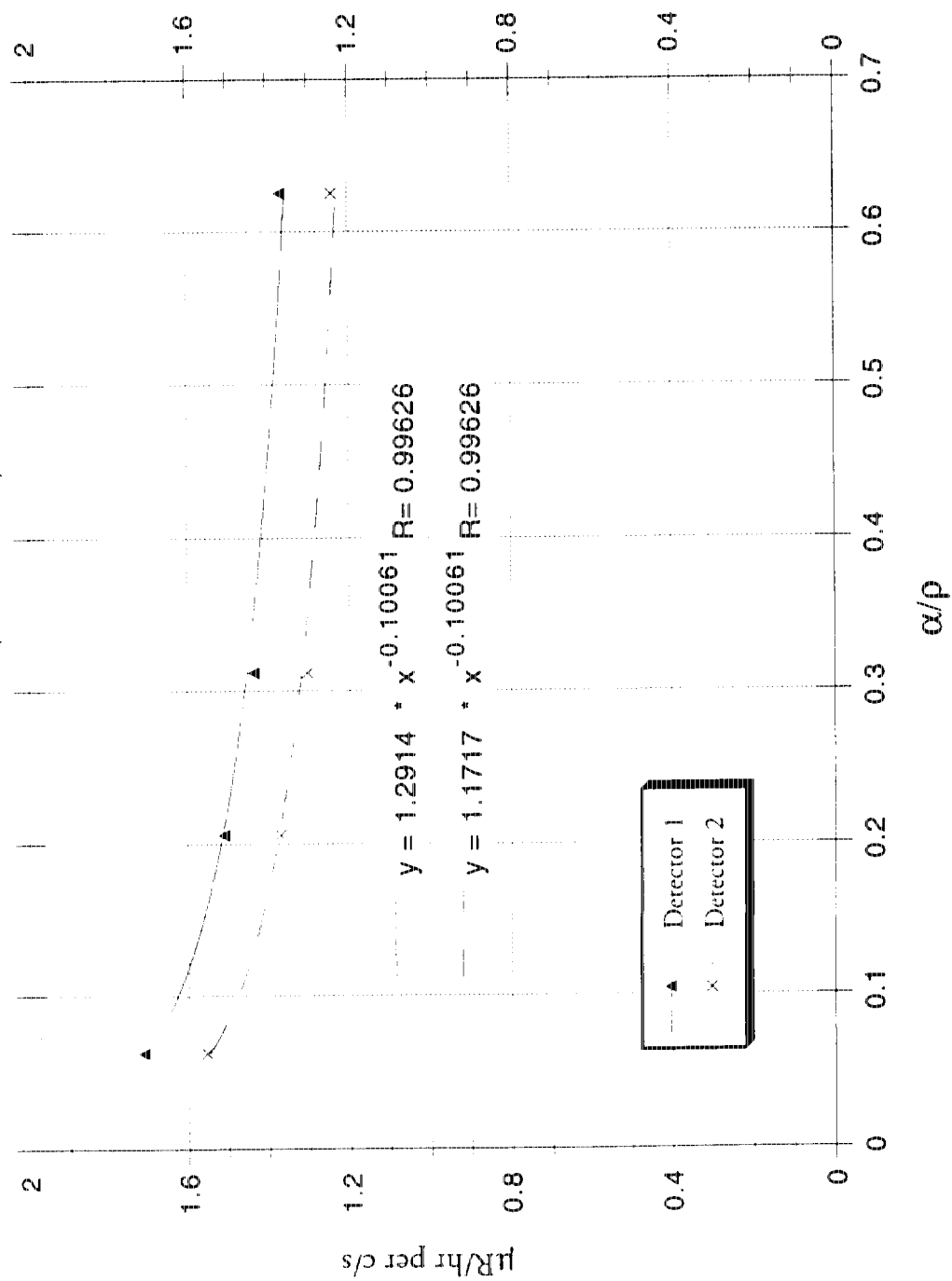


Fig. 2 $\mu\text{R/hr per c/s for }^{60}\text{Co}$
Method 1 (Beck 1972)



APPENDIX A3, SECTION (ii)

METHODOLOGY: Detection limits, Gamma spectrometry methodology,
Gamma spectrometry error calculations, Plutonium measurement methodology,
Alpha spectrometry error calculations

S. L. Simon, J. C. Graham and A. Borchert

ESTIMATION OF MINIMUM DETECTION LIMITS**I. *In-Situ* count-rates**

The minimum detectable count-rate (c/s in full energy peak) for *in-situ* measurements for ^{137}Cs was calculated for the maximum *in-situ* count time of 2 hours. The average peak channel (number 1552) and region-of-interest (ROI) width (41 channels) was determined from 10 randomly selected *in-situ* spectra. Ten spectra were selected with count-rates less than 0.01 c/s in the ^{137}Cs ROI. Using the average peak channel and peak width, the average background integral count-rate for ^{137}Cs was determined to be 0.022 c/s. The minimum detectable full energy peak count-rate was then calculated to be 0.0085 c/s using the following equation:

Minimum detectable peak count-rate (c/s) =

$$= \frac{(\sqrt{\text{Bkg}} \cdot 4.65) + 2.71}{7200 \text{ s}} = \frac{(\sqrt{158.4} \cdot 4.65) + 2.71}{7200 \text{ s}} = 0.0085 \text{ c/s}$$

where:

Bkg = background integral counts in 2 hours (0.022 c/s x 7200 s)

II. Laboratory Concentrations

Minimum detectable concentrations (MDC) for laboratory measurements were calculated for ^{137}Cs , ^{241}Am and ^{60}Co . The MDC for these nuclides was calculated in units of Bq/kg and converted to areal inventory in the environment (Bq/m²).

The detector efficiency for the radionuclides of interest was determined using a radioactive sand source made in the RMI Laboratory. Marshall Islands soil with low organic matter content was spiked with a liquid radioactivity standard traceable to the National Institute of Standards

and Technology (NIST). The background integral peak counts for the maximum count time (12 hours) was calculated for the three radionuclides using 5 background spectra and 5 sample spectra. The sample spectra were used to determine the median peak channel and median number of channels in the radionuclide region-of-interest (ROI). This information was used with the 5 background spectra to determine the background integral counts in the radionuclide ROI. The minimum peak area counts in 12 hours per kg was determined from the following equation:

$$\text{MDcounts} = \frac{(\sqrt{\text{Bkg} \times 4.65}) + 2.71}{m \epsilon}$$

where,

MDcounts is the minimum detectable counts in the full energy peak area

Bkg = background integral counts in 12 hours

m = sample mass (kg)

ϵ = detector efficiency for the full energy peak

The minimum detectable concentration (Bq/kg) was determined using the equation:

$$[\text{MDC}]_{\text{mass}} = \frac{\text{MDc} / R}{t}$$

where,

$[\text{MDC}]_{\text{mass}}$ is the minimum detectable concentration in units of Bq/kg

R = the radionuclide branching ratio for the gamma photon energy

t = the count time in seconds (12 hours = 43200 s)

The $[\text{MDC}]_{\text{areal}}$ (Bq/m²) was calculated using the following equation:

$$[\text{MDC}]_{\text{areal}} = [\text{MDC}]_{\text{mass}} \times 50$$

where,

$[\text{MDC}]_{\text{areal}}$ is the minimum detectable areal activity in units of Bq/m²

50 = the conversion from Bq/kg to Bq/m² for a 5 cm profile increment using a density of 1 g/cm³.

Using the calculations above the MDC (mass and areal) for the three radionuclides was calculated and is found in the following table.

Radionuclide	MDC (Bq/kg)	MDC (Bq/m ²)
²⁴¹ Am	2.0	100
¹³⁷ Cs	0.3	15
⁶⁰ Co	0.2	10

The minimum detectable concentration for ^{239,240}Pu was not calculated because of procedures used in our laboratory that depend on the anticipated concentration of the radionuclide in the sample. In methods which we have devised, the concentration of ²⁴¹Am is first estimated in soil samples by gamma spectrometry. The concentration of ^{239,240}Pu is then estimated from the ²⁴¹Am concentration using an empirical relationship established from previous samples. The soil sample mass for plutonium determination is then calculated so that a count-rate will be obtained such that 90% precision can be reached in a 12 hour counting time. Thus, very low concentration samples are compensated by using a larger amount of sample. In some cases, soil samples with low anticipated concentrations are split and run through several extraction columns to keep the columns from becoming saturated. The maximum amount of soil sample that can be used and the maximum number of columns that can be used to give reliable results has not been determined. However, the minimum concentration measured in our laboratory for ^{239,240}Pu is on the order 0.04 Bq/kg or 2 Bq/m². Using the method described above, this concentration was determined with 90% precision ($\pm 10\%$).

SUMMARY OF GAMMA SPECTROMETRY METHODOLOGY

In-Situ Gamma Spectrometry

The amount of ¹³⁷Cs activity in the soil at each atoll was first estimated from either literature information or by interpolation or extrapolation from nearby islands or atolls. The estimated ¹³⁷Cs soil activity was used to estimate the length of the *in-situ* count time to reach 90% precision (commonly called 10% counting statistics). We determined that peak errors less than or equal to 10% were considered adequate for our data analysis purposes. In the most contaminated locations, some *in-situ* measurements obtained a peak error of less than 10% in 1 minute or less. In these cases, counting time was normally extended to a minimum of 5 minutes while data sheets were completed for the *in-situ* measurement site. A maximum count time of 2 hours was set so as to ensure that a sufficient number of measurements could be conducted during a 10 day field trip.

Supplies of liquid nitrogen which could be carried on board ship for the hyper-pure germanium (HPGe) detectors was one consideration in setting the field trip length.

Laboratory Gamma Spectrometry

Approximately 3500 samples were counted in the RMI Radiation laboratory on two HPGe detectors. One limitation of the RMI Radiological Study was the number of samples that could be counted on the 2 detectors. The minimum count time depended on the ^{137}Cs and ^{241}Am peak count-rates. Counting of samples was generally stopped when 90% precision or greater (10% counting statistics or less) was reached. Some samples required less than 2 hours for the ^{137}Cs and ^{241}Am peaks to reach this level of precision. Other samples were counted for up to 12 hours or until the ^{137}Cs peak error reached 90% precision or greater (10% or less counting statistics).

Peak Area and Error Calculations¹

The area algorithm computes the net number of counts in a region-of-interest (ROI), i.e., the number of counts above the average background within the ROI. To determine the average background count-rate in the ROI, the ROI is separated into the peak and side channels outside the peaks. The algorithm used in our analysis system for the Background Area averages K points on either side of the peak (K is usually equal to 3), then calculates a straight line between the two averaged values.

$$\text{Net Area} = \text{Integral} - \text{Background Area}$$

The Integral is the total number of counts in the current ROI. The ROI is defined to extend from the ROI's start channel to the ROI's stop channel, inclusive:

$$\text{Integral} = \sum_{a=u}^v X_a$$

where,

u = the ROI's start channel

v = the ROI's stop channel

X_a = counts in channel a

The Background Area is the average of the number of counts among the ROI's channels in the absence of any peak:

¹ The System 100 User's Manual. Version 3.0, 1987-1990. Canberra, Industries, Inc.

$$\text{Background Area} = C_d/2 \times (B_1 + B_2)$$

where

C_d = the number of data channels

$$B_1 = \text{Averaged height of the background on the left} = \left[\sum_{a=u}^{u+K+1} X_a \right] K$$

$$B_2 = \text{Averaged height of the background on the right} = \left[\sum_{a=v-K+1}^v X_a \right] K$$

u = the ROI's start channel

v = the ROI's stop channel

K = 4, the number of end-points considered

Percent Error

Percent Error signifies the precision (often called counting statistics) of the area calculation. The percent error is automatically calculated by the computerized counting system in the following way.

$$\% \text{ Error} = \frac{m\sigma}{\text{area}} \times 100$$

where,

m = 1.65, the confidence level in sigma units.

$$\sigma = \sqrt{G + (N/2)^2 (1/K) (B_1 + B_2)}$$

In the above equation, G is determined as:

$$G = \sum_{a=u+K}^{v-K} X_a$$

where,

G = the gross counts in the peak

N = the number of channels in the peak = $C_d - 2K$

C_d = the number of data channels

- K = 4, the number of end-points considered
 B_1 = Averaged height of the background on the left
 B_2 = Averaged height of the background on the right
 u = the ROI's start channel
 v = the ROI's stop channel
 X_a = counts in channel a

ERROR ANALYSIS FOR GAMMA SPECTROMETRY MEASUREMENTS

Laboratory Measurements

- I. Conversion from count-rate of standard (Marinelli beaker geometry) to activity of standard

$$\begin{aligned}
 \frac{Bq}{c/s} &= \frac{x \pm \sigma_x}{c \pm \sigma_c} = \frac{x}{c} \pm \sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2 + 2 \rho_{xc} \sigma_x \sigma_c \frac{x}{c}} \left(\frac{x}{c}\right) \\
 &= \frac{x}{c} \pm \epsilon_{xc}
 \end{aligned}$$

$\frac{x}{c}$ has units of Bq per c/s.

- II. Conversion from count-rate of sample to activity of sample

$$\begin{aligned}
 \left[\frac{x}{c} \pm \epsilon_{xc}\right] [s \pm \sigma_s] &= \frac{xs}{c} \pm \sqrt{\left(\frac{\epsilon_{xc}}{x/c}\right)^2 + \left(\frac{\sigma_s}{s}\right)^2} \left(\frac{xs}{c}\right) \\
 &= \frac{xs}{c} \pm \epsilon_{xcs}
 \end{aligned}$$

$\frac{xs}{c}$ has units of Bq and is the activity of the sample.

- III. Conversion from activity of sample to concentration in sample

$$\left[\frac{x \text{ s}}{c \text{ m}} \pm \epsilon_{xcs} \right] (1/m) = \frac{x \text{ s}}{c \text{ m}} \pm \frac{\epsilon_{xcs}}{m}$$

$\frac{x \text{ s}}{c \text{ m}}$ has units of Bq/g and is the concentration of the sample.

IV. Conversion from concentration in sample (Bq/g) to areal inventory in a single depth increment (i.e., Bq/m² in 5 cm thick increment).

$$\begin{aligned} & \left[\frac{x \text{ s}}{c \text{ m}} \pm \frac{\epsilon_{xcs}}{m} \right] [1 \text{ g/cm}^3 \pm 0.2 \text{ g/cm}^3] [5E4 \text{ cm}^3 \text{ per m}^2 \text{ per 5 cm thickness}] = \\ & = \left[\frac{x \text{ s}}{c \text{ m}} \pm \frac{\epsilon_{xcs}}{m} \right] (1 \pm 0.2) (5E4) \end{aligned}$$

$$= 5E4 \frac{x \text{ s}}{c \text{ m}} \pm \sqrt{\left(\frac{\epsilon_{xsc}/m}{x \text{ s}/c \text{ m}} \right)^2 + \left(\frac{0.2}{1} \right)^2} \left(\frac{5E4 x \text{ s}}{c \text{ m}} \right)$$

$$= a \pm \epsilon_a$$

'a' has units of Bq/m² and is the areal inventory of a single 5 cm thick increment.

IV. Conversion from areal inventory (Bq/m²) in a single 5 cm thick increment (increment 'i') to areal inventory (Bq/m²) in total depth profile from 0 to 30 cm depth.

$$\sum_{i=1}^6 (a \pm \epsilon_a)_i = \sum_{i=1}^6 a_i \pm \sqrt{\sum_{i=1}^6 \epsilon_{ai}^2 + 2 \rho_{12} \epsilon_{a1} \epsilon_{a2} + \dots}$$

$$= a_T + \epsilon_T$$

In the above equation, ρ_{12} is approximately equal to 1.0. Note that there are additional cross product terms under the square root sign, i.e., $(\rho_{13} \epsilon_{a1} \epsilon_{a3})$, $(\rho_{14} \epsilon_{a1} \epsilon_{a4})$, $(\rho_{15} \epsilon_{a1} \epsilon_{a5})$, $(\rho_{16} \epsilon_{a1} \epsilon_{a6})$, $(\rho_{21} \epsilon_{a2} \epsilon_{a1})$, etc.

'a_T' has units of Bq/m² and is the total areal inventory for the depth profile from 0 to 30 cm.

In-Situ Measurements

Estimates of areal inventory of ^{137}Cs (Bq/m^2) are determined from the product of the *in-situ* measured count-rate (c/s) and an empirically determined calibration factor (Bq/m^2 per c/s). The determination of the calibration factor used data (i.e., Bq/m^2) from 194 soil profiles which were counted in the laboratory and in-situ measurements (i.e., c/s) at the same location. The analysis of this data is discussed in Appendix A3(i) though a summary is provided below. The calibration factor data set ($n=194$) is close to a lognormal distribution. Note the closeness of the sample median and the geometric mean in the table below. A log-probability plot of the calibration factors data (see Appendix A3(i)) also confirms the closeness of the data set to log-normality.

The confidence limits for the median of a lognormal distribution are provided by Gilbert (1987, eq. 13.20):

$$\frac{\exp(\bar{y})}{[\exp(s_{\bar{y}})]^{t_{1-\alpha/2, n-1}}} \leq \exp(\mu_y) \leq \exp(\bar{y}) [\exp(s_{\bar{y}})]^{t_{1-\alpha/2, n-1}}$$

where $\exp(\mu_y)$ is the geometric mean, $\exp(s_{\bar{y}})$ is the sample geometric standard error and $t_{1-\alpha/2, n-1}$ is obtained from a table of quantiles of the t-distribution (e.g., Table A2, Gilbert 1987). The sample summary statistics are shown below.

sample mean.....	5504.4
standard deviation...	5742.7
sample median.....	4060.0
geometric mean.....	4047.7
geometric standard deviation.....	2.15
sample size.....	194
sample geometric standard error.....	1.06

The 1 sigma confidence interval on the median, therefore, is approximately: $\frac{4060}{1.06^{0.86}}$ to $(4060 \times 1.06^{0.86})$ or 3861 to 4244 Bq/m^2 per c/s . The relative error on the median value of the calibration factor, " Bq/m^2 per c/s " about 6%

The total error on the areal inventory is the combined error resulting from the product of the calibration factor (Bq/m^2 per cps) and the in-situ count rate:

$$\left[\frac{\text{Bq}/\text{m}^2}{\text{c/s}} \pm \sigma \right] \times [\text{c/s} \pm \sigma_{\text{c/s}}] = \text{Bq}/\text{m}^2 \pm \sqrt{\left(\frac{\sigma}{\text{Bq}/\text{m}^2 \text{ per c/s}} \right)^2 + \left(\frac{\sigma_{\text{c/s}}}{\text{c/s}} \right)^2} \left[\frac{\text{Bq}/\text{m}^2}{\text{c/s}} \times \text{c/s} \right]$$

$$= \text{Bq/m}^2 \pm \sigma_{\text{Bq/m}^2}$$

In the equation above, the counting error is determined from the in-situ data [see data tables in Appendix A3(iv)].

REFERENCES

Gilbert, R. O. 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold Co., New York. Chapter 13.

MEASUREMENT OF PLUTONIUM IN CORAL BASED SOIL¹

Soil Preparation:

- 1) Following sample collection, dry soil to required level of dryness.
- 2) Remove 25 grams of well-mixed soil and place in a tared medium size ceramic crucible. (Watch out for soil clinging to the lid of the storage container.)
- 3) Record the exact dry weight of the sample; 25 g is used in this procedure.
- 4) Wipe the crucible and the storage container off with a wet towel.
- 5) Cover the crucible and place sample in a muffle furnace. Ramp the temperature up to 200°C for 2 hours, then ash at 840°C for several hours/overnight to remove organic component of the soil. (Make sure you draw a sample arrangement map of the samples in the oven because the sample number will be burnt off during muffling.)
- 6) After cooling, remove the samples from the muffle furnace and write the correct sample number on each crucible.

Soil Leaching I:

- 1) Transfer the soil to a 250 mL heavy duty beaker. Use a polypropylene policeman to transfer as much sample as possible. Added about 10 mL of distilled water to moisten the soil. (This will allow the addition of concentrated HNO₃ without splattering.) Place the polypropylene policeman in the center of the beaker while holding it up right and slowly pour 100 mL of concentrated HNO₃ down it's side until the reaction comes to equilibrium. Using a Pasteur pipet, add 5 mL of concentrated HNO₃ to the crucible, then use the polypropylene policeman to scrape the sides. Rinse the crucible three times with concentrated HNO₃ and transfer the washings into the beaker.
- 2) Cover the beaker with a Speedy-Vap cover. (This will help eliminate cross contamination.)
- 3) Place the sample on a hot plate and heat the sample at high heat.
- 4) As the HNO₃ boils off, the sample will become pasty; at this point add 5 mL of 30% H₂O₂. (This process helps get rid of any left over organic components.)
- 5) Heat the sample to near dryness.
- 6) The sample should be whitish in color although some samples may have a yellowish color indicating iron.

Soil Leaching II:

- 1) Redissolve the sample with 50 mL of concentrated HNO₃, if needed use a polypropylene policeman to break up any undissolved particles.
- 2) Place the redissolved sample on a hot plate and boil for several minutes to allow for sufficient leaching.
- 3) Boil off the HNO₃ until the sample becomes pasty, at this point add 5 mL of 30% H₂O₂.
- 4) Heat the sample to near dryness, then redissolve the sample in 50 mL of 8 M HNO₃.
- 5) Decant the sample from the beaker to a 100 mL graduated cylinder, wash the beaker 3 to 4X with 8 M HNO₃ or until the final volume reaches 100 mL. The sample is now dissolved as 25 g soil per 100 mL solution.

¹developed in consultation with Dr. Shawki Ibrahim, Department of Radiological Health Sciences, Colorado State University, Ft. Collins, CO.

Determine Aliquot Size for Extraction:

1) The Aliquot size in this method is determined by several factors, most importantly, the estimated $^{239,240}\text{Pu}$ concentration of the sample and the desired count time. The preferred counting time is 6 to 8 hours or less. Accordingly, the sample activity and the tracer must have sufficient activity such that a reasonable level of precision is reached within the time interval.

The aliquot size used and the amount of tracer added, are both chosen so that the measurement achieves at least 90% precision (at the 1 sigma confidence level) within the 6-8 hour time frame. The required amount of tracer to do this is about 8 to 10 dpm. The aliquot size is estimated such that the activity of the tracer and the activity of the sample are approximately equal and will, therefore, reach about the same level of precision within the counting interval. The required aliquot size can be determined by first estimating the plutonium activity of the sample from the enclosed figure and the ^{241}Am activity as measured by gamma spectrometry. The aliquot weight (g) is then determined from the following equation:

$$\frac{\text{Number of counts need to get at least 10\% counting statistics}}{(\text{Estimated } ^{239,240}\text{Pu dpm/g}) \times (\text{Average chemical yield}) \times (\text{Detector efficiency}) \times (\text{Desired count time})}$$

2) From the dissolved sample (25 g /100 mL) pipet an aliquot equal to the sample weight needed, i.e; if the desired sample weight is 1.25 g, then pipet an aliquot of 5 mL of the dissolved sample into a beaker.

3) Spike the sample with the amount of tracer as noted above.

NOTE: Samples may now go on through the column extraction procedure or they may be co-precipitate. Co-precipitation may or may not be needed depending on the clarity of the sample solution. If sample clarity is good proceed to the Column Extraction procedures.

Calcium Oxalate Co-Precipitation:

1) Place the spiked sample into a 250 mL Teflon beaker.

2) While stirring, add concentrated NH_4OH dropwise until pH is about 4. The pH can be monitored with indicator paper. The solution will be slightly cloudy.

3) Add oxalic acid in an amount roughly equivalent to the original weight of the soil sample. Heat the solution, but do not boil.

4) Add 2 to 3 mL of NH_4OH to bring the pH back to about 4 by checking with pH paper. Bring solution to a low boil for 5 minutes.

5) Remove from heat and cool to room temperature. Filter the solution through a medium flow, ashless filter paper. Discard the supernate.

6) Place the filter and filtrate in a heavy duty, 250 mL glass beaker. Cover with a porcelain crucible cover and dry at 80 to 100 °C. (Overnight drying is fine.)

7) Place the dried sample in a muffle furnace at 200°C for 2 hours, then muffle it at 550°C for at least 8 hours.

8) Remove the beaker from the muffle furnace and add about 20 mL of concentrated HNO_3 acid, heat the solution on a hot plate until the solution becomes pasty, at this point add 5 mL of H_2O_2 to ash the sample free from organics.

9) Heat the sample to dryness and redissolve in 25 ml of 8 M HNO_3 . The sample is now ready for column extraction.

Column Extraction:

- 1) Set up the plastic columns with added reservoir. Add approximately 4 grams per sample of SIGMA DOWEX 1 column resin (only use the strongly basic anion exchanger type, 50-100 dry mesh in it's chloride form) into approximately equal amount of 8 M HNO_3 until a slurry is formed.
- 2) Wash the anion exchange column with 8 M HNO_3 until the wash is chloride free. To test if the wash is chloride free, put a few drops of the 8 M HNO_3 into a clean beaker and add a few drops of a 10% solution of AgNO_3 . A white precipitate indicates that the wash still has chloride within it, if this is the case, continue to wash with 8 M HNO_3 until no precipitate is produced.
- 3) Sample should now be dissolved in 25 mL of 8M HNO_3 . Add a pinch of sodium nitrite, then run the sample solution through the column at the rate of 1 drop per second. (If sample is to be analyzed for americium, the wash should be saved.)
- 4) Wash the column with 3 to 5 volumes of 8 M HNO_3 (200 mL of 8 M HNO_3 removes americium)
- 5) Wash the column with 3 to 5 volumes of 9 M HCl (Removes thorium).
- 6) Elute the plutonium using 60 mL of ammonium iodide reagent.
- 7) Add 3-5 drops of concentrate H_2SO_4 to the solution.
- 8) Place the sample on a hot plate on high heat and evaporate the solution to near dryness.
- 9) Add concentrated HNO_3 and evaporate while periodically adding a few drops of 30% peroxide. When dryness is approached, add more concentrated nitric, then allow to evaporate to dryness. (This will oxidize the iodine salts which are formed as the sample evaporates.)

RECIPES

Oxalate Co-Precipitation

10% Oxalic Acid

10 g oxalic acid/100 mL

Column Extraction

8M HNO_3

water to acid ratio of 1 to 1

9M HCl

water to acid ratio of 1 to 3

Ammonium Iodide Reagent (11M HCl + 0.1M NH₄I)

Volume mL	HCL mL	H ₂ O mL	NH ₄ I grams
60	55	5	0.864
100	91.67	8.33	1.44
120	110	10	1.72
180	165	15	2.59
240	220	20	3.456
300	275	25	4.32
360	330	30	5.18

AgNO₃ (10%)

5g/50 mL

MICROPRECIPITATION: NEODYMIUM FLUORIDE MOUNTING

- 1) Dissolve the prepared plutonium sample in 1 or 2 mL of 1M HCl.
- 2) Transfer the solution to a plastic centrifuge tube. Wash the original sample vessel 3X with 1 mL washes of 1M HCl. Use a rubber policeman to scrub the beaker and to aid in the transfer of the washings to the centrifuge tube, then gently shake the mixture.
- 3) Add 100 μ L of the 0.5 mg/mL Nd carrier solution to the tube with a micropipet dispenser. Mix.
- 4) Add 10 drops (0.5 mL) of 48% HF to the tube and mix well.
- 5) Place the tube in a cold-water ice bath for at least 30 minutes.
- 6) Insert the polysulfone filter stem into the seven outlet vacuum manifold. Put the support screen in place.
- 7) Prepare the filtration apparatus by placing a 25 mm Tuffryn filter on the support screen. (Place the dull side of the filter face up. The filters are usually shipped that way, but should be visually inspected anyway.)
- 8) Pull a weak vacuum, then wet the filter with 80% ethyl alcohol.
- 9) Lock the filter chimney in place. Open the vacuum to full.
- 10) Wash with 80% ethyl alcohol, followed by a filtered, deionized water wash.
- 11) Draw 10 mL of neodymium substrate solution into a plastic pipet.
- 12) Add 5 mL of the neodymium substrate solution down the side of the filter chimney. Allow the filter to suck dry for 15 seconds. Repeat with the remaining 5 mL of substrate solution.
- 13) Add 25 mL of filtered, deionized water to the sample solution. Place in ultrasonic bath for one minute.
- 14) Pour the sample down the side of the filter chimney and allow to suck dry.
- 15) Add about 5 mL of 0.58N HF to the tube and place in ultrasonic bath for two minutes. Pour the wash down the filter chimney. Repeat 2X.
- 16) Add 5 mL of filtered, deionized water to the tube and put in ultrasound bath again. Pour the wash down the filter chimney. Repeat 2X.

17) Wash down any drops remaining on the chimney sides with 80% ethyl alcohol. (Do not disturb the precipitate by pouring directly onto the filter.)

18) Without turning off the vacuum, remove the filter chimney.

19) Reduce or turn off the vacuum. Place the filter onto the mounting disc. Discard the filtrate.

20) Dry the filter under a heat lamp for several seconds prior to counting.

RECIPES

Microprecipitation Stock

- 1) 20 L filtered, de-ionized water
- 2) 1 N HCL (5 liter)
- 3) Neodymium carrier (1000 µg/mL)
- 4) 48% HF
- 5) ETOH (100%)

1 N HCL

Add 83.3 mL of concentrated HCL to 916.7 mL of distilled H₂O

Neodymium Carrier Solution: 0.5 mg/mL

10 mL stock into 20 mL total

Neodymium Fluoride Substrate: 10 mg/Liter

5 mL neodymium stock 460 mL of 1N HCL 40 mL of 48% HF

0.58N HF

Add 20 mL 48% HF to 980 mL of H₂O 980 mL

80% ETOH

ETOH : Water in the ration of 80 to 20

ERROR PROPAGATION FOR ALPHA SPECTROMETRY MEASUREMENTS

(1) Dilution of spiking solution to make tracer

$$\begin{aligned}
 \text{SWAd} \pm \sigma_{\text{SWAd}} &= (\text{WB} \pm \sigma_{\text{WB}}) - (\text{WA} \pm \sigma_{\text{WA}}) \\
 &= (\text{WB} - \text{WA}) \pm \sqrt{\sigma_{\text{WB}}^2 + \sigma_{\text{WA}}^2} \quad **(\text{see Footnote 1}) \\
 \\
 \text{SAcAd} \pm \sigma_{\text{SAcAd}} &= (\text{SWAd})(\text{SC}) \pm \sqrt{\left(\frac{\sigma_{\text{SWAd}}}{\text{SWAd}}\right)^2 + \left(\frac{\sigma_{\text{SC}}}{\text{SC}}\right)^2} [(\text{SWAd})(\text{SC})] \\
 &\quad **(\text{see Footnote 2}) \\
 \\
 \text{TC} \pm \sigma_{\text{TC}} &= \frac{(\text{SAcAd} \pm \sigma_{\text{SAcAd}})}{(\text{L} \pm \sigma_{\text{L}})} \\
 &= \frac{\text{SAcAd}}{\text{L}} \pm \sqrt{\left(\frac{\sigma_{\text{SAcAd}}}{\text{SAcAd}}\right)^2 + \left(\frac{\sigma_{\text{L}}}{\text{L}}\right)^2} \left[\frac{\text{SAcAd}}{(\text{L})} \right]
 \end{aligned}$$

where,

SWB	≡	solution weight before (g)
SWA	≡	solution weight after (g)
SWAd	≡	solution weight added (g)
SC	≡	solution concentration (dpm/g)
SAcAd	≡	solution activity added (dpm/g)
L	≡	amount of liquid of diluted solution (ml), i.e., tracer + acid
TC	≡	tracer concentration (i.e., of diluted solution, dpm/g)

NOTE: All error terms (σ 's) have the same units as variable to which it applies, not percentage. The range of plus or minus one sigma (σ) should be considered as equal to the 67% confidence interval and inclusive of the known random errors.

¹ σ_{WB} and σ_{WA} \equiv 0.0001 g as determined by precision of laboratory analytical balance

² σ_{SC} was determined from manufacturer's standardization

(2) Spiking of sample with tracer

$$\begin{aligned}
 \text{TWAd} \pm \sigma_{\text{TWAd}} &= (\text{TWB} \pm \sigma_{\text{TWB}}) - (\text{TWA} \pm \sigma_{\text{TWA}}) \\
 &= (\text{TWB} - \text{TWA}) \pm \sqrt{\sigma_{\text{TWB}}^2 + \sigma_{\text{TWA}}^2} \quad **(\text{see Footnote 3}) \\
 \text{SA} \pm \sigma_{\text{SA}} &= (\text{TWAd} \pm \sigma_{\text{TWAd}}) (\text{TC} \pm \sigma_{\text{TC}}) \\
 &= \sqrt{\left(\frac{\sigma_{\text{TWAd}}}{\text{TWAd}}\right)^2 + \left(\frac{\sigma_{\text{TC}}}{\text{TC}}\right)^2} [(\text{TWAd})(\text{TC})]
 \end{aligned}$$

where,

TWB	≡	tracer weight before (g)
TWA	≡	tracer weight after (g)
TWAd	≡	tracer weight added (g)
SA	≡	spike activity (dpm)

(3) Determination of sample concentration, detector efficiency and chemical yield

$$\begin{aligned}
 \epsilon \pm \sigma_{\epsilon} &= \frac{\text{CSt} \pm \sigma_{\text{CSt}}}{(\text{DSt} \pm \sigma_{\text{DSt}}) t_{\text{st}}} \\
 &= \frac{\text{CSt}}{\text{DSt} t_{\text{st}}} \pm \sqrt{\left(\frac{\sigma_{\text{CSt}}}{\text{CSt}}\right)^2 + \left(\frac{\sigma_{\text{DSt}}}{\text{DSt}}\right)^2} \left[\frac{\text{CSt}}{\text{DSt} t_{\text{st}}} \right] \\
 Y \pm \sigma_Y &= \frac{(\text{CTr} \pm \sigma_{\text{CTr}})}{t_{\text{sa}}(\epsilon \pm \sigma_{\epsilon}) (\text{SA} \pm \sigma_{\text{SA}})} \\
 &= \frac{\text{CTr}}{t_{\text{sa}} \epsilon \text{ SA}} \pm \sqrt{\left(\frac{\sigma_{\text{CTr}}}{\text{CTr}}\right)^2 + \left(\frac{\hat{1}}{\epsilon \text{ SA}}\right)^2} \left[\frac{\text{CTr}}{t_{\text{sa}} \epsilon \text{ SA}} \right]
 \end{aligned}$$

³ σ_{TWB} and $\sigma_{\text{TWA}} \equiv 0.0001$ g as determined by precision of laboratory analytical balance

$$\text{Co} \pm \sigma_{\text{Co}} = \frac{(\text{CSa} \pm \sigma_{\text{CSa}}) (\text{SA} \pm \sigma_{\text{SA}})}{(\text{CTr} \pm \sigma_{\text{CTr}}) (\text{WU} \pm \sigma_{\text{WU}})}$$

$$= \frac{(CSa) (SA)}{(CTr) (WU)} \pm \sqrt{\left(\frac{\hat{2}}{CSa SA}\right)^2 + \left(\frac{\hat{3}}{CTr WU}\right)^2} \left[\frac{(CSa) (SA)}{(CTr) (WU)}\right]$$

where,

$$\hat{1} \equiv \sqrt{\left(\frac{\sigma_{\epsilon}}{\epsilon}\right)^2 + \left(\frac{\sigma_{SA}}{SA}\right)^2} \quad [(\epsilon)(SA)]$$

$$\hat{2} \equiv \sqrt{\left(\frac{\sigma_{CSa}}{CSa}\right)^2 + \left(\frac{\sigma_{SA}}{SA}\right)^2} \quad [(CSa)(SA)]$$

$$\hat{3} \equiv \sqrt{\left(\frac{\sigma_{CTr}}{CTr}\right)^2 + \left(\frac{\sigma_{WU}}{WU}\right)^2} \quad [(CTr)(WU)]$$

ϵ \equiv counting efficiency (including intrinsic detector efficiency, geometry, etc.)

CS_t \equiv counts of standard

t_{st} \equiv time for counting of standard (min)

D_{st} \equiv Disintegration rate of standard (dpm)

Y \equiv chemical yield

CT_r \equiv counts of tracer

CS_a \equiv counts of sample

t_{sa} \equiv time for counting of sample (min)

Co \equiv concentration of radionuclide

APPENDIX A3, SECTION (iii)

RESULTS OF A MEASUREMENT INTERCOMPARISON BETWEEN THE RMI
NATIONWIDE RADIOLOGICAL STUDY AND LAWRENCE LIVERMORE
NATIONAL LABORATORY

J. C. Graham and S. L. Simon

Several different intercomparisons were performed between the RMI Nationwide Radiological Study and the Lawrence Livermore Laboratory (LLNL, a contractor of the U.S. Department of Energy). This process was important to the Rongelap Resettlement Project because one objective was to verify or confirm previously reported data from the U.S. Department of Energy and its contractor laboratories.

One comparison made was among 12 soil profiles sampled on Rongelap Island. These 12 sites were selected by Dr. Steve Simon and excavated using a DOE backhoe during the course of a field trip in November of 1991. After excavation, LLNL personnel collected soil samples from depth increments of 0-5 cm, 5-10 cm, 10-15 cm, 15-25 cm, 25-40 cm and 40-60 cm. Personnel from the RMI Radiological Study then collected soil samples from the same excavation pit from depths 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm and 25-30 cm. In this particular case, the LLNL and RMI personnel collected samples independently rather than splitting a single sample.

The preparation procedures of the two groups varied slightly. In the preparation of the soils for gamma counting, LLNL removed all particles >2 mm. The RMI laboratory, however, did not remove any size particles prior to counting but rather crushed the large particles to a smaller but uniform particle size.

Only the top three layers of the profiles were used for the comparison because of the differences in sampling depths for the deeper layers. The concentration (Bq/g) of ^{137}Cs measured by the RMI Radiological Study was divided by the concentration (Bq/g) of ^{137}Cs as reported by LLNL. The average and median ratios (i.e., RMI/LLNL) for the 36 samples was calculated to be 0.79 and 0.62, respectively. The addition of the large particles by the RMI Radiological Study laboratory likely added very little radioactivity, thus diluting the sample compared to the LLNL procedures. The net effect would be a lower average concentration for the RMI data relative to the LLNL data. This effect is verified by the average and median ratios which are less than 1.0. However, it should be noted that even with the differences in the soil preparation, the average and median ratios compare fairly well.

Profile samples were also collected from Rongelap Atoll jointly by LLNL and RMI personnel during August of 1993. A total of 77 profile samples were collected. These profile samples were

mixed in the field and split between the RMI and LLNL laboratories. The concentration (Bq/g) of ^{137}Cs measured by the RMI Radiological Laboratory was again divided by the concentration (Bq/g) of ^{137}Cs measured by LLNL. The RMI laboratory measured 57 of these samples using the DOE soil processing procedures, i.e., without particles > 2 mm in size. All 77 samples were also measured with the particles > 2 mm size. The median and average ratio and the number of samples are given in the table below. From the data shown in the table it can be seen that the median and average ratios between the laboratories for the samples without particles > 2 mm agree very well. The values for the RMI samples that included the > 2 mm particles are lower as expected.

	Median	Average	N
0-5 cm depth increment			
With Particles > 2 mm	0.74	0.66	13
Without Particles > 2 mm	0.97	1.22	8
0-10 cm depth increment			
With Particles > 2 mm	0.60	0.62	26
Without Particles > 2 mm	0.94	1.03	18
0-30 cm depth increment			
With Particles > 2 mm	0.60	0.60	77
Without Particles > 2 mm	0.87	0.95	57

Data of the ^{137}Cs concentration in the top 5 cm of soil from the grid locations on Rongelap Island was also compared. These samples had been obtained during field trips conducted in November of 1991 and April of 1992 though the LLNL and RMI laboratories collected and analyzed samples independently from one another. LLNL reported concentrations (pCi/g) of ^{137}Cs in the top 5 cm of soil; we converted these values to units of Bq/kg. The RMI concentration data (Bq/kg) data for ^{137}Cs in surface soil samples from the grid locations was again divided by the LLNL data and the median and average values calculated. From the 56 samples, the median and mean ratios were, 0.83 and 1.2, respectively.

Samples from plants were also measured by LLNL and the RMI laboratory and compared. Three pandanus fruit samples, four plant leaf samples (of specified species) and 24 coconut samples were used in this comparison. The coconut samples included the juice and meat collected from 12 individual trees. Each tree had one juice sample and one meat sample. For the 31 plant samples, the median and average ratio of concentrations (RMI/LLNL) were calculated to be 1.0

and 1.1, respectively. A minimum and maximum ratio of 0.83 and 1.57, respectively, was observed.

A comparison was also made between the exposure-rates reported by the U.S. DOE from an aerial survey of the northern Marshall Islands in 1978 and those calculated from data acquired by the RMI Radiological Study. The external exposure rates (measured in mR/h) from ^{137}Cs reported by the DOE¹ were compared to the RMI data at approximately the same locations (i.e., as well as could be determined). The RMI exposure rate data was calculated from our *in-situ* gamma spectrometry measurements and decay corrected to the same date as the DOE data. The RMI data was divided by the DOE data at each location and an average ratio for each island was calculated. The median and average ratio for 283 locations on 27 islands on Rongelap Atoll was calculated to be 1.07 and 1.32, respectively. The individual ratio values at each island (i.e., RMI value/DOE value) are shown on Figure 1. A probability plot of the ratios from all locations in Rongelap Atoll which could be compared are shown in Figure 2. The data in both figures are centered about a ratio of approximately unity.

All five comparisons with the LLNL showed quite good agreement. The comparisons made included data resulting from different types of samples and different preparation methods. The differences that were observed in the ratios is believed to be mainly related to sample preparation and sampling variability.

¹Tipton W.J., R.A. Meibaum. 1978. An aerial radiological and photographic survey of eleven atolls and two islands within the northern Marshall Islands. EG&G for the U.S. DOE Division of Operational and Environmental Safety. EGG-1183-1758.

Fig. 1 Ratio of ^{137}Cs soil inventory (Bq/m^2) at Rongelap Atoll:
RMI in-situ spectrometry estimates (1994)/ DOE-EG&G aerial survey (1978, decay corrected)

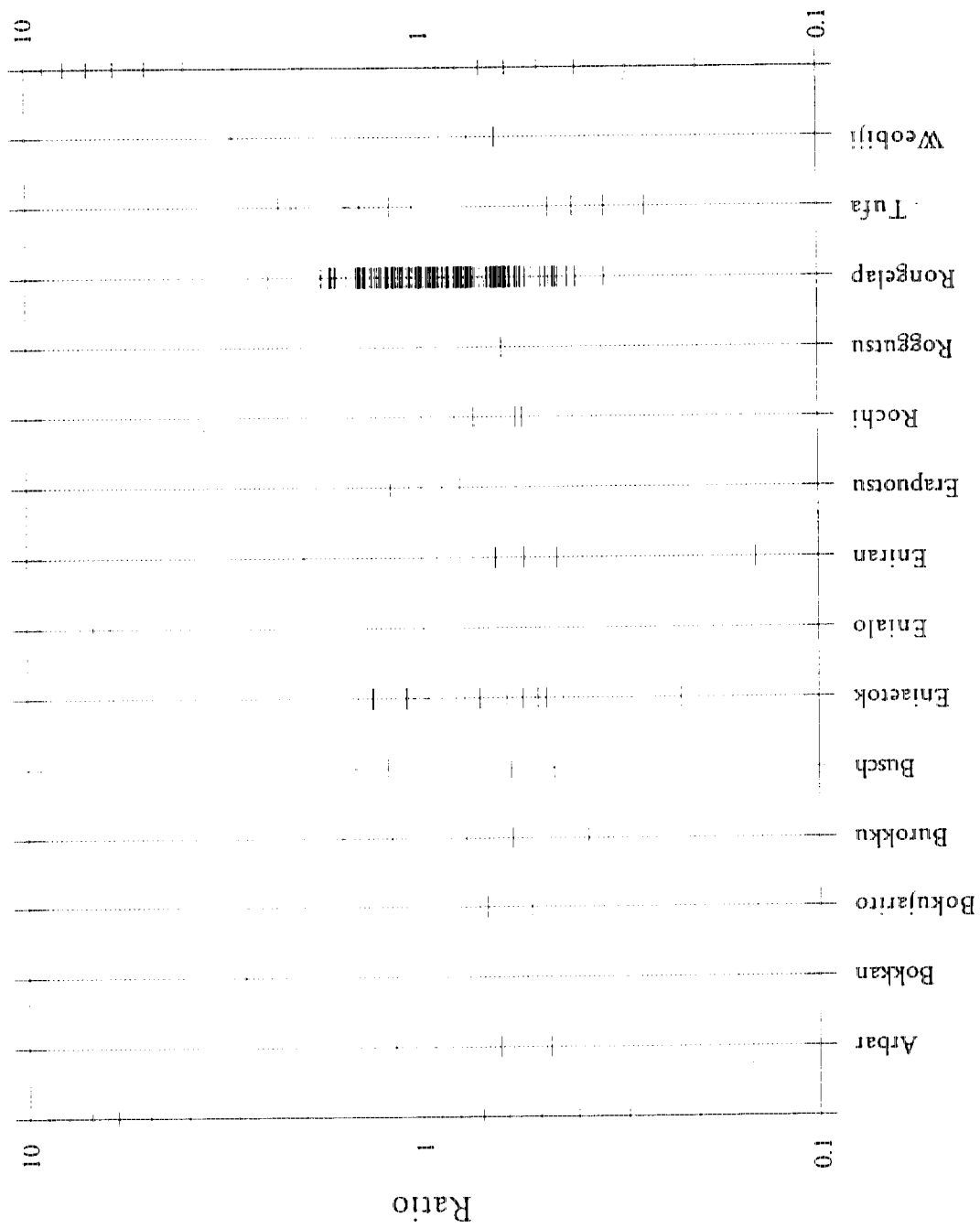
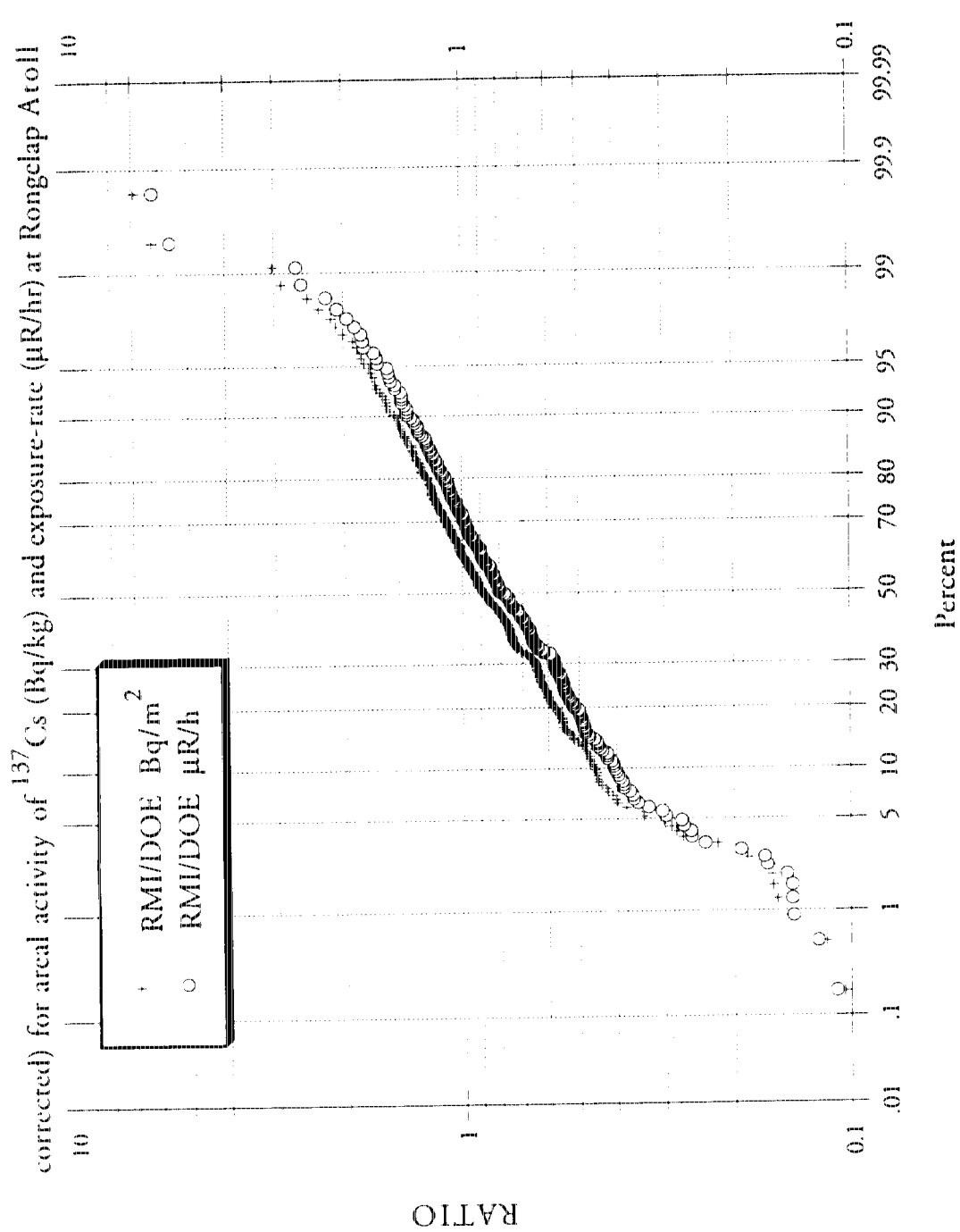


Figure 2. Probability plot of ratio of RMI data (1994) to DOE aerial survey data (1978, decay-



APPENDIX A3, SECTION (iv)

RADIOLOGICAL SURVEY FINDINGS:

List of Island Names

Sampling Maps

Soil Profile Results

Table of Radiological Data from Rongelap Survey

Probability Distributions of Radioactivity Measurement Data in Local Foods

Small Grid Interpolation Maps

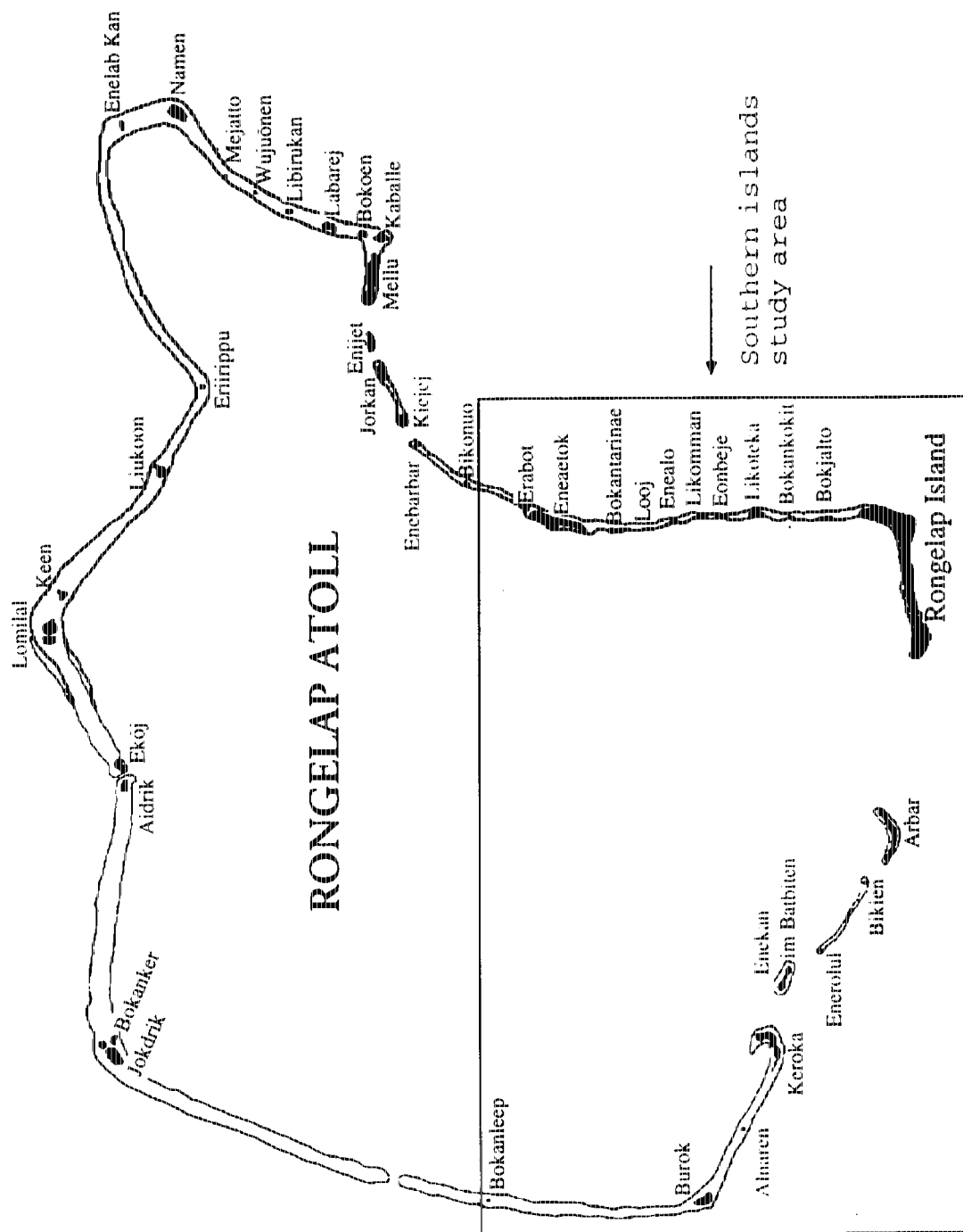
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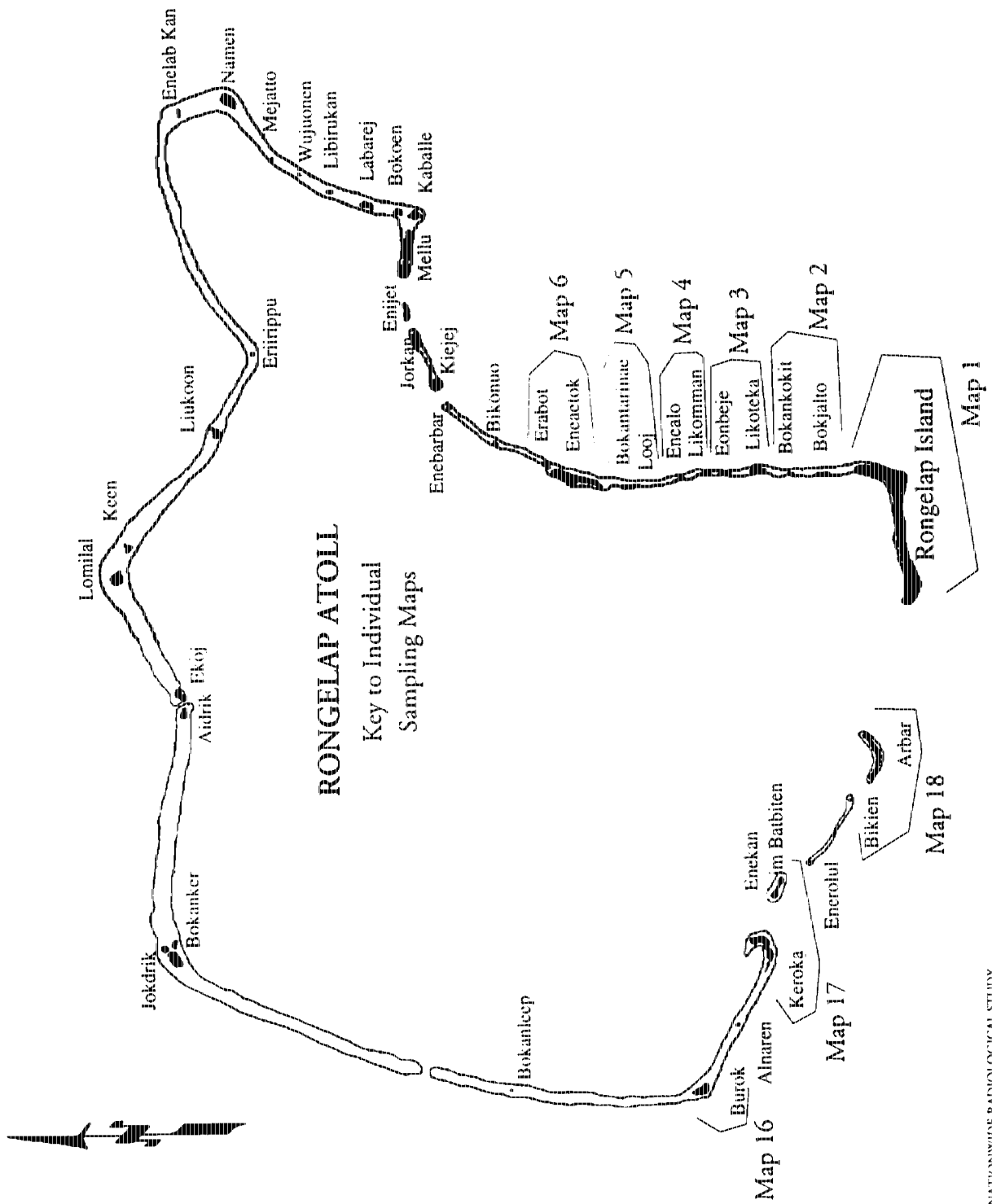
COMPARISON OF ISLAND NAMES IN RONGELAP ATOLL

Island name from navigation chart (Japanese origin)	Marshallese names of islands used in this report ¹
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Rongelap	Rongelap
Bokujarito	Bokjalto
Roggutsu	Bokankokit
Busch	Likoteka
Weobiji	Eonbeje
Rigonman	Likomman
Enialo	Enealo
Rochi	Looj
Bogontorinaai	Bokantarinae
Eniaetok	Eneaetok
Erapuotsu	Erabot
Bigannuo	Bikōnuo
Enybarbar	Enebarbar
Kieshiechi	Kiejej
Gogan	Jorkan
Anidjet	Enijet
Mellu	Mellu
Gabelle	Kabelle
Bokoēn	Bokoēn
Labaredj	Labarej
Ribiyurgan	Libirukan
Yuzugan	Wujuōnen
Mejatto	Mejatto
Kabelle	Namen
Anielap	Enelab Kan
Eriirippu	Eriirippu
Lukuen	Likoon
Gejen	Keen
Lomuila	Lomila
Yugui	Ekōj
Aerik	Aidrik
Yugui	Bokanker
Piganiyaroyaro	---
Naen	Jokdrik
Pokoreppu	Bokanleep
Burok	Burok
Arugaren	Alnaren
Tufa	Keroka
Eniran	Enekan im Batbiten
Eniroruuri	Enerolul
Bikien	Bikien
Arbar	Arbar

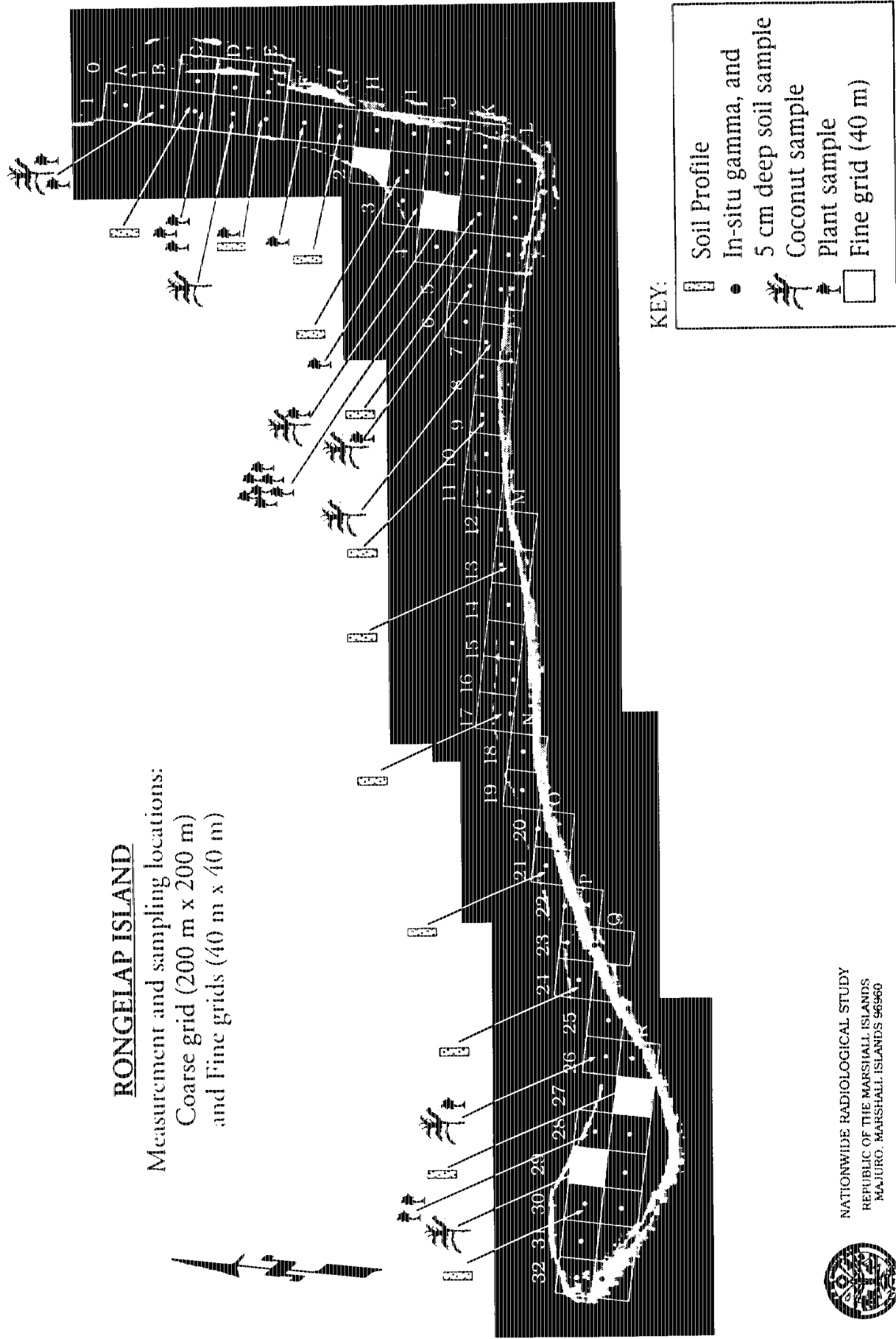
¹Names supplied by Mr. Randy Thomas of Rongelap

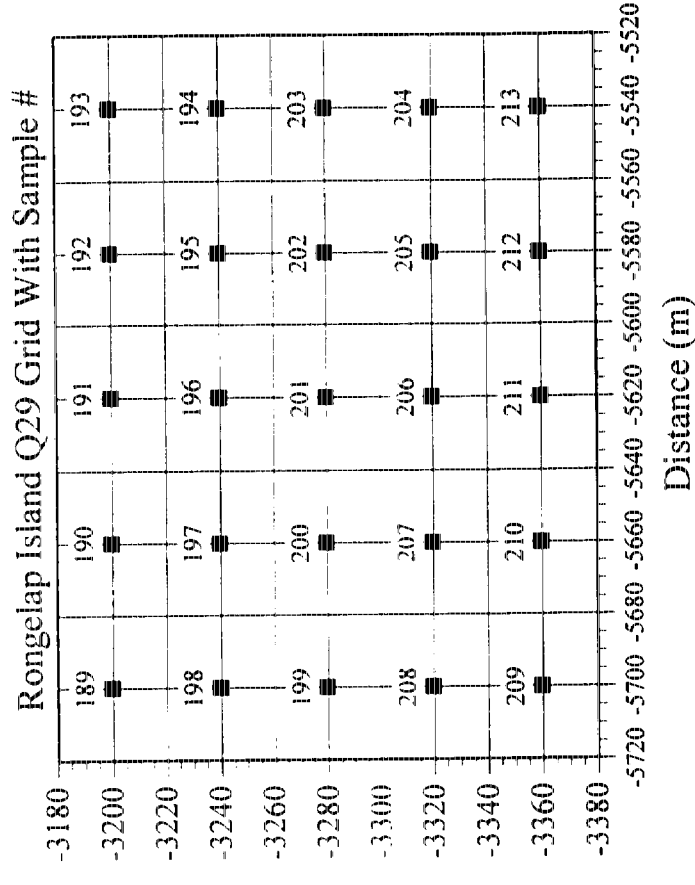
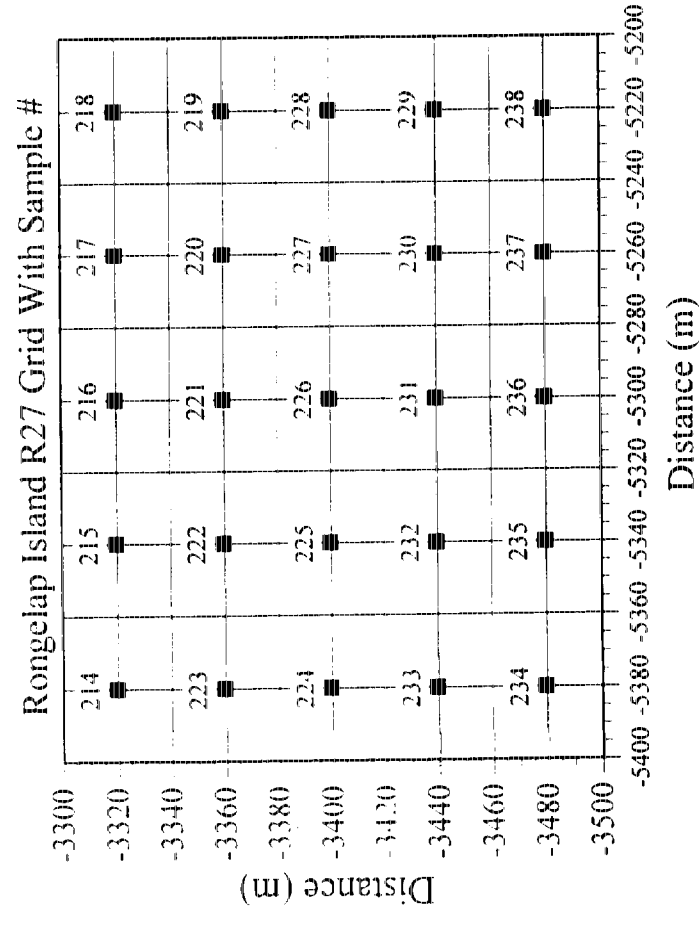
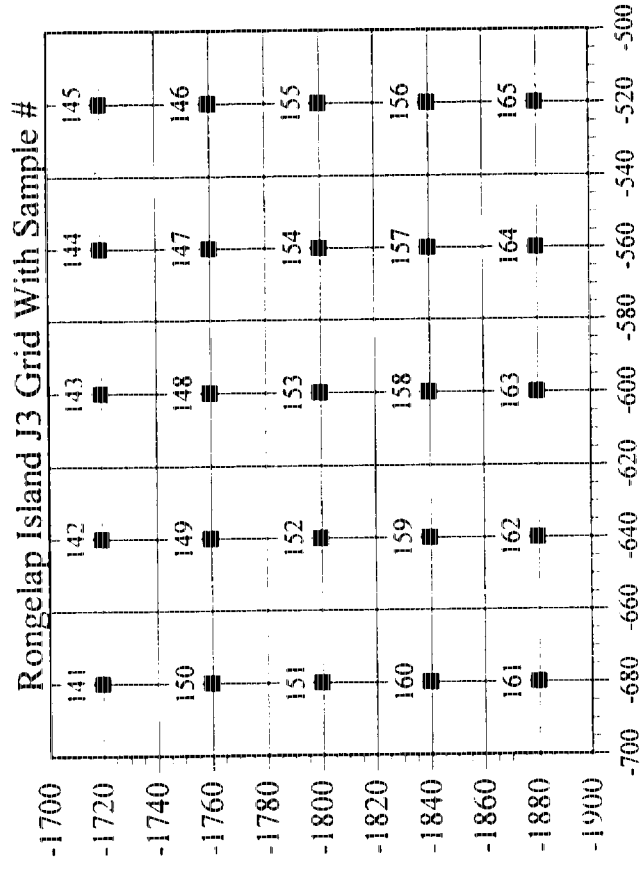
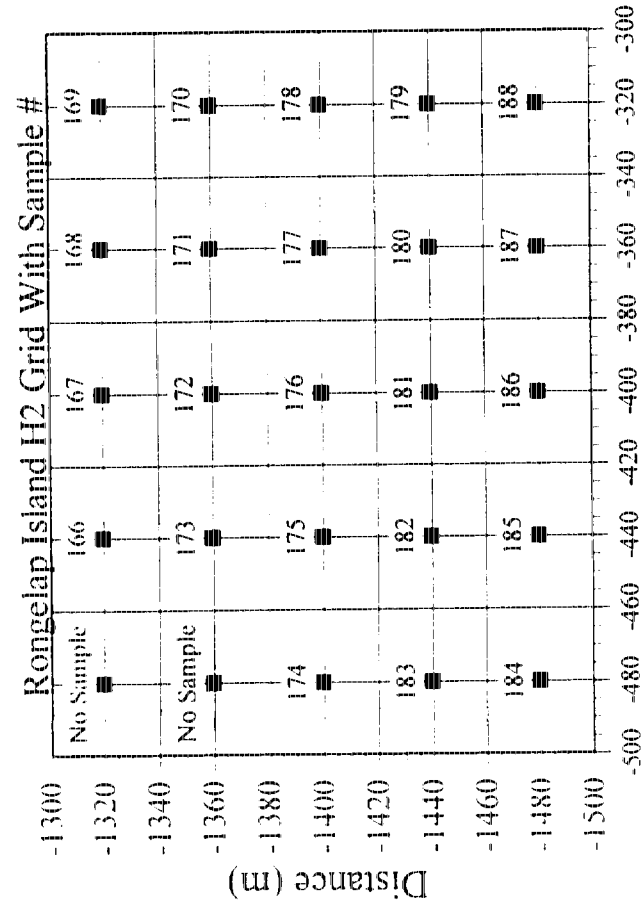


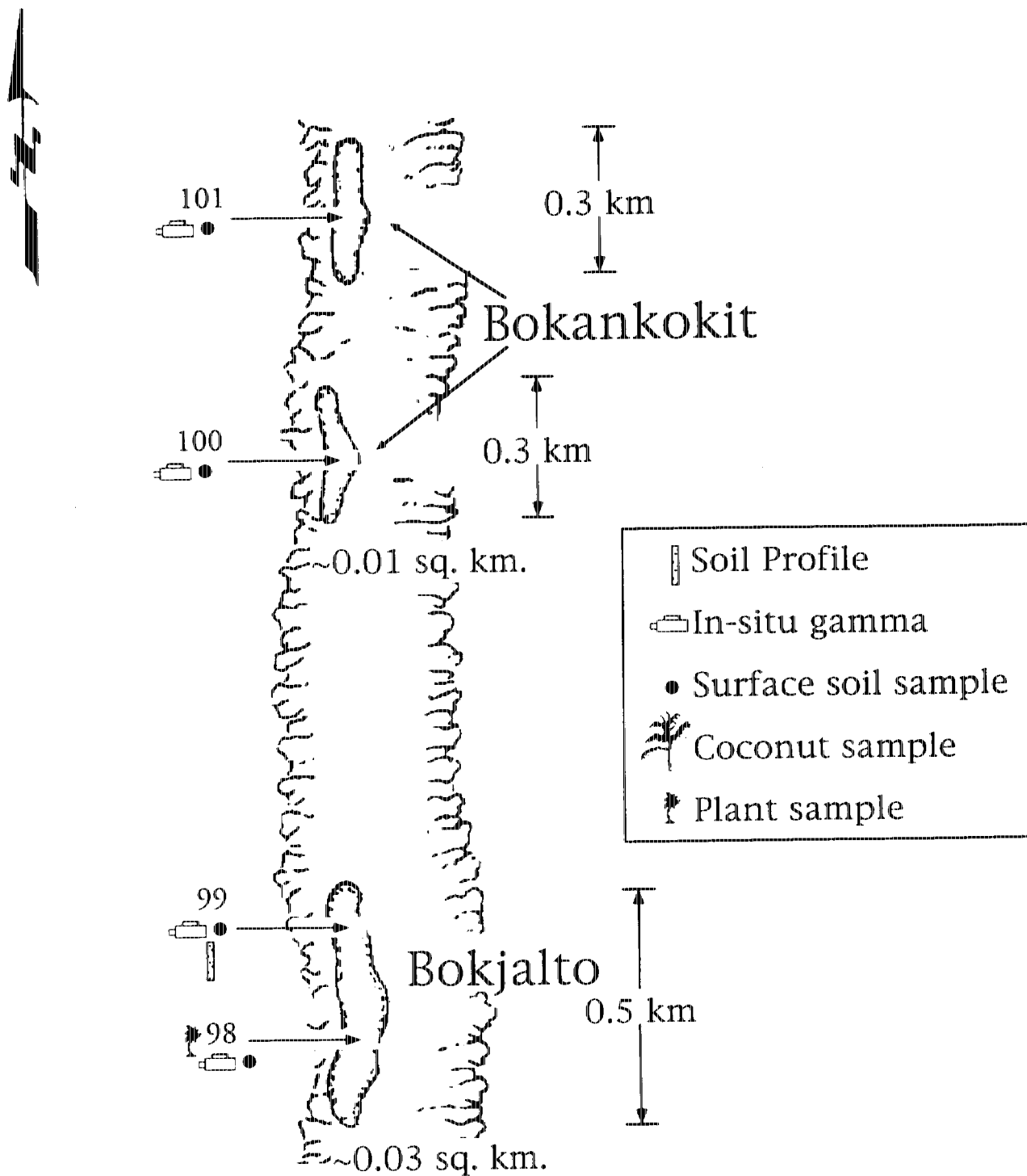


RONGELAP ISLAND

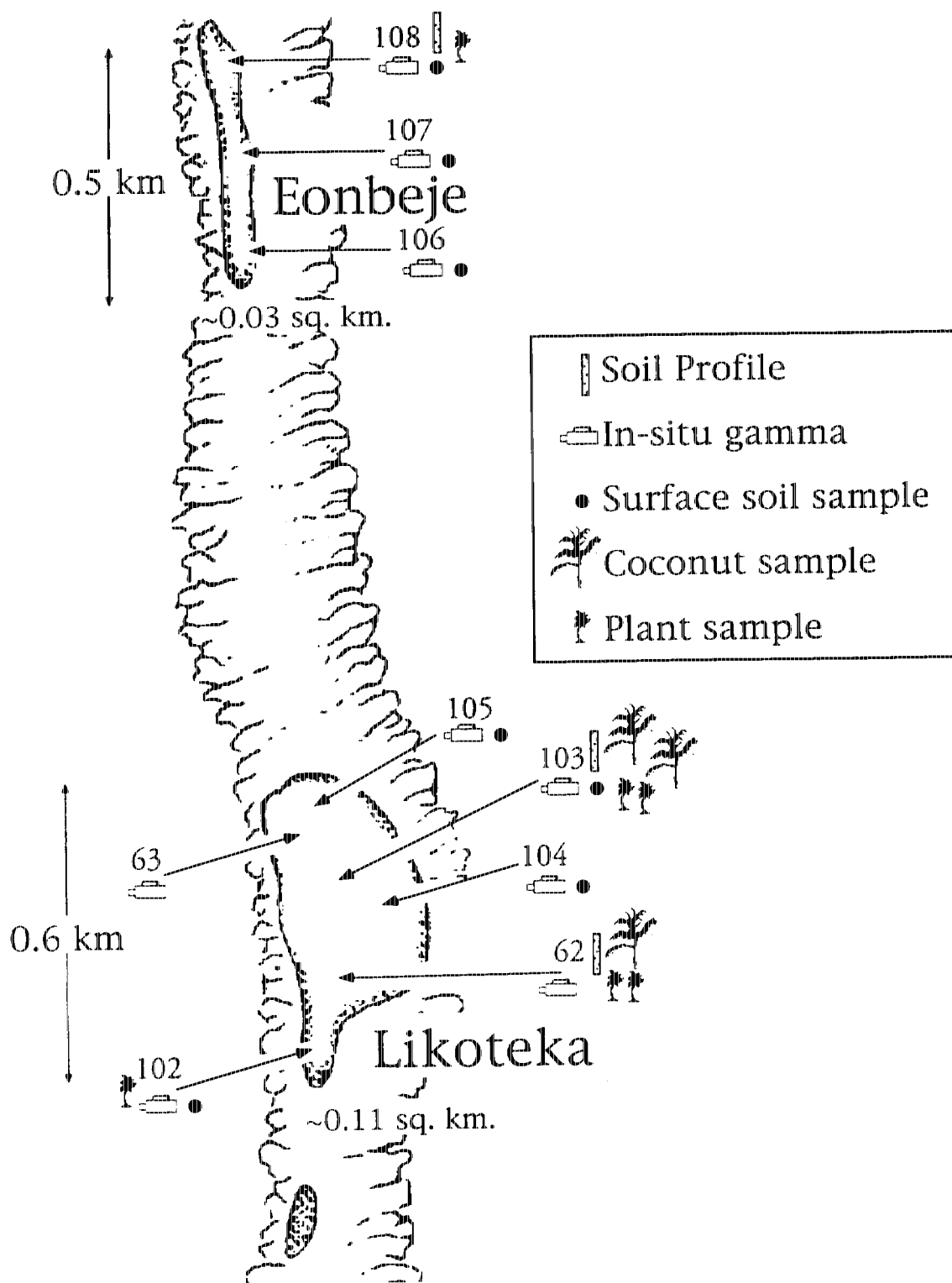
Measurement and sampling locations:
Coarse grid (200 m x 200 m)
and Fine grids (40 m x 40 m)



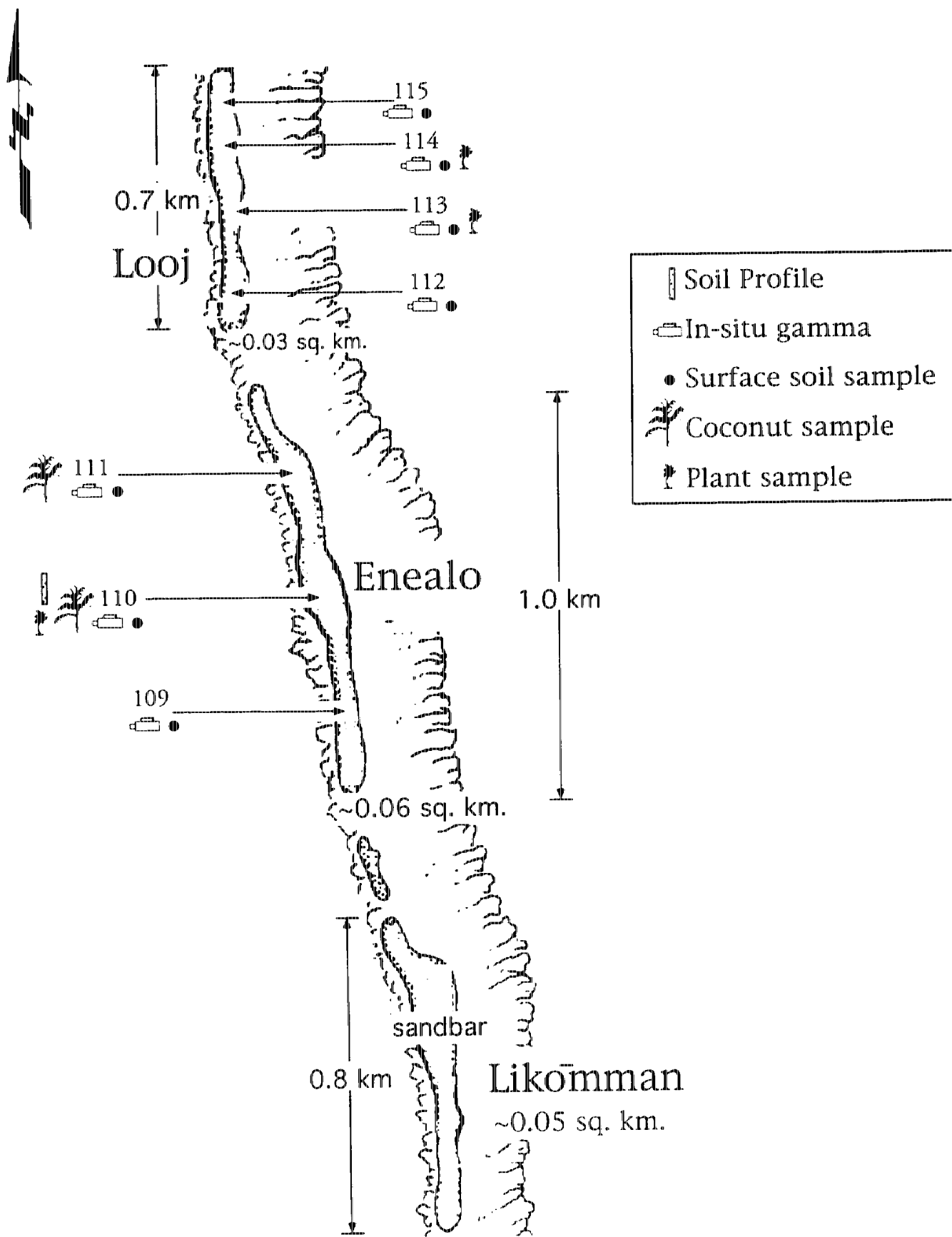




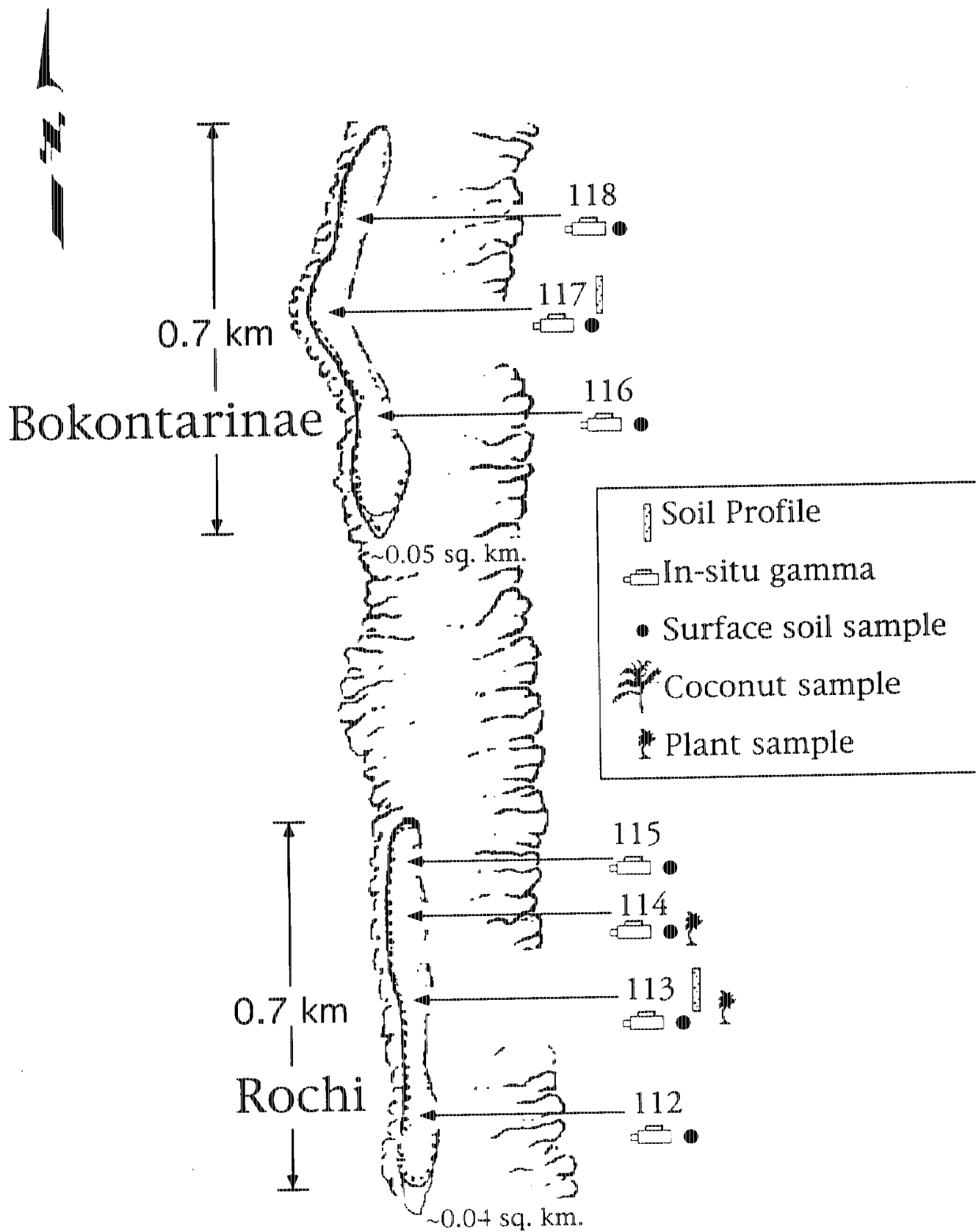
RONGELAP Map 2
(200 m x 200 m sampling grid)



RONGELAP Map 3
(200 m x 200 m sampling grid)

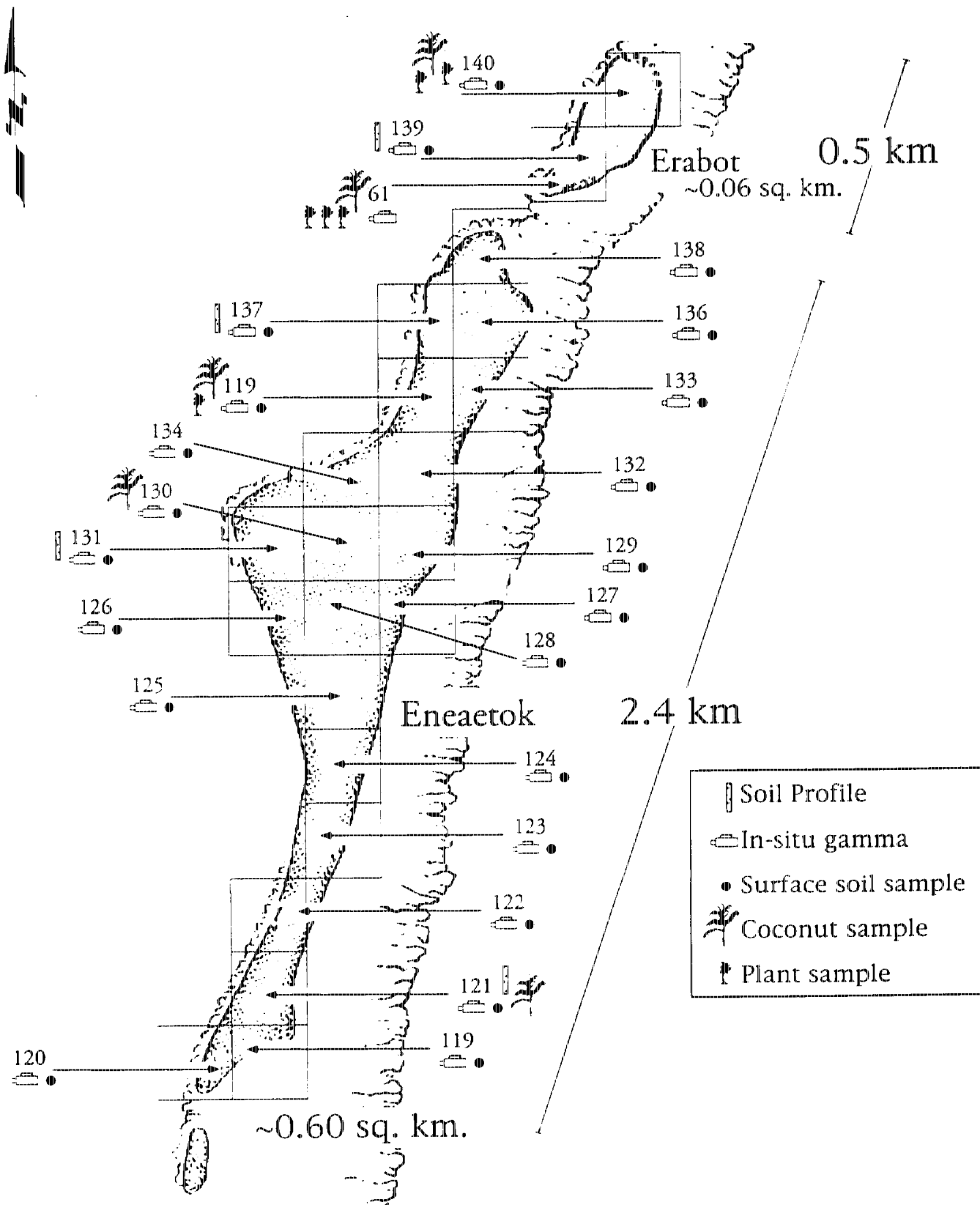


RONGELAP Map 4
(200 m x 200 m sampling grid)

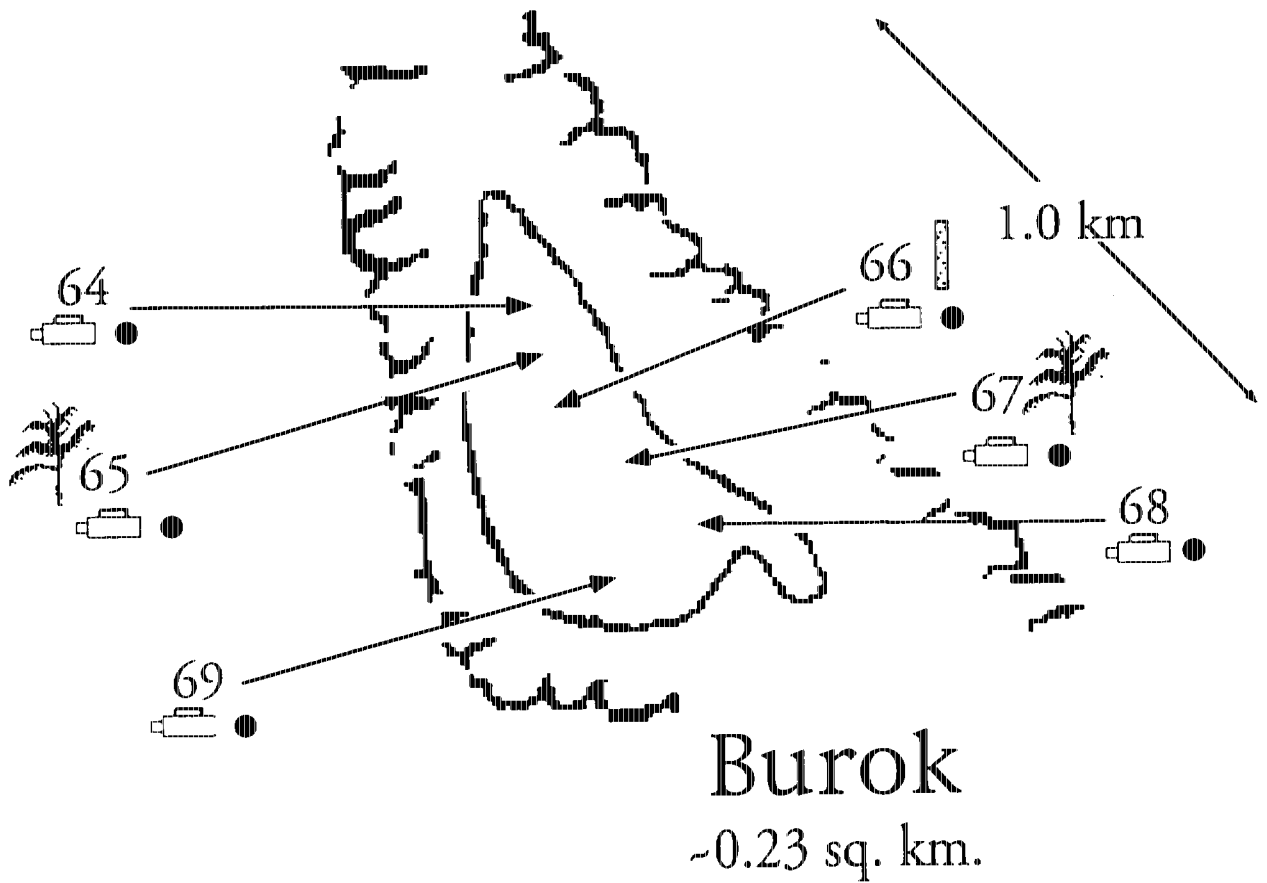
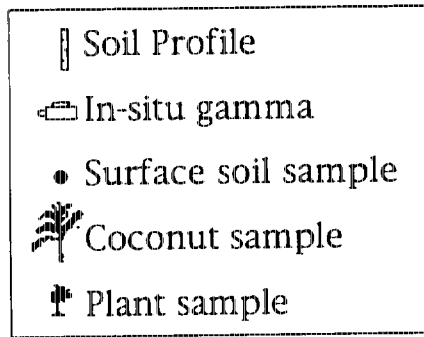


Rongelap Map 5

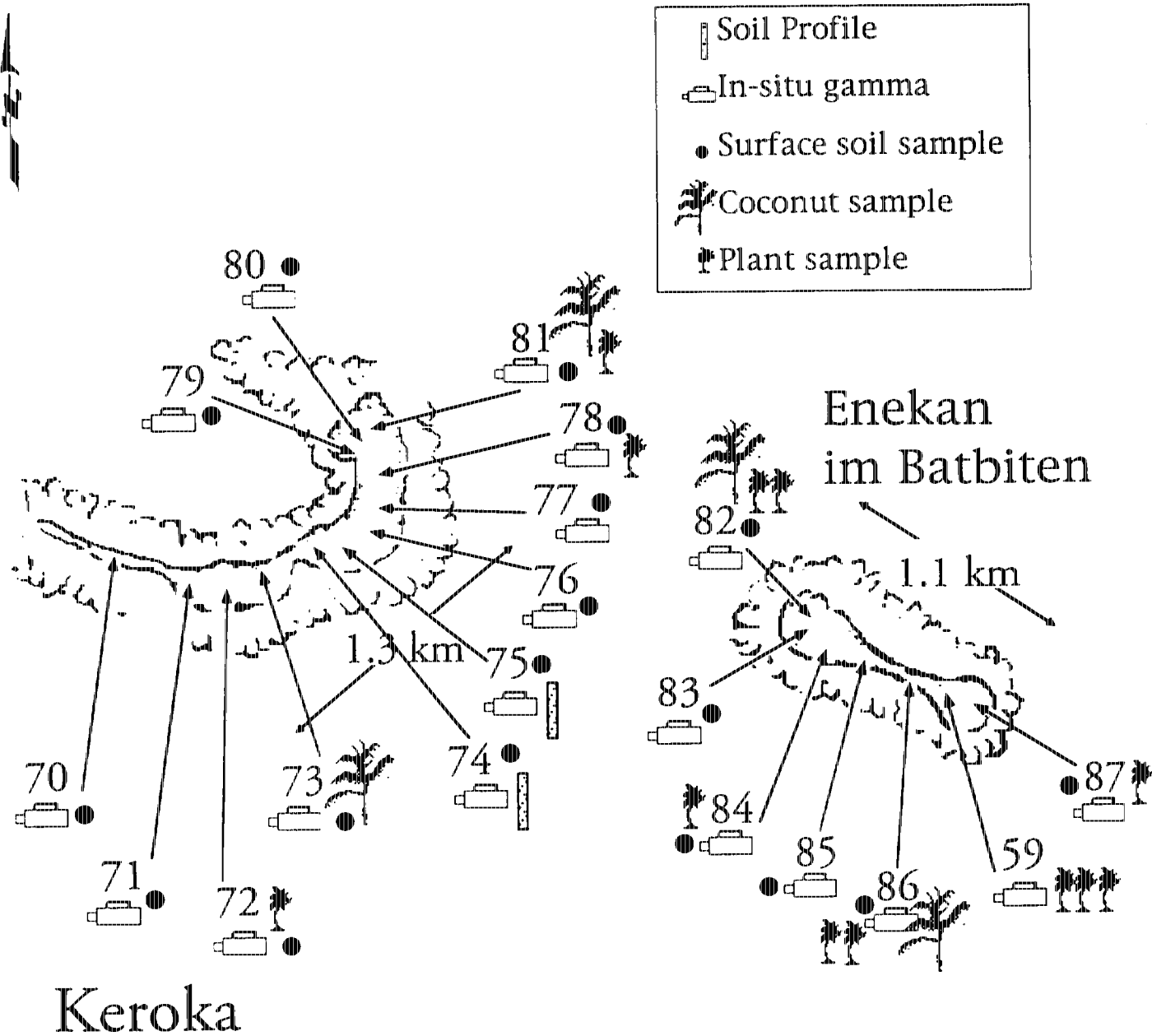
(200 x 200 m sampling grid)



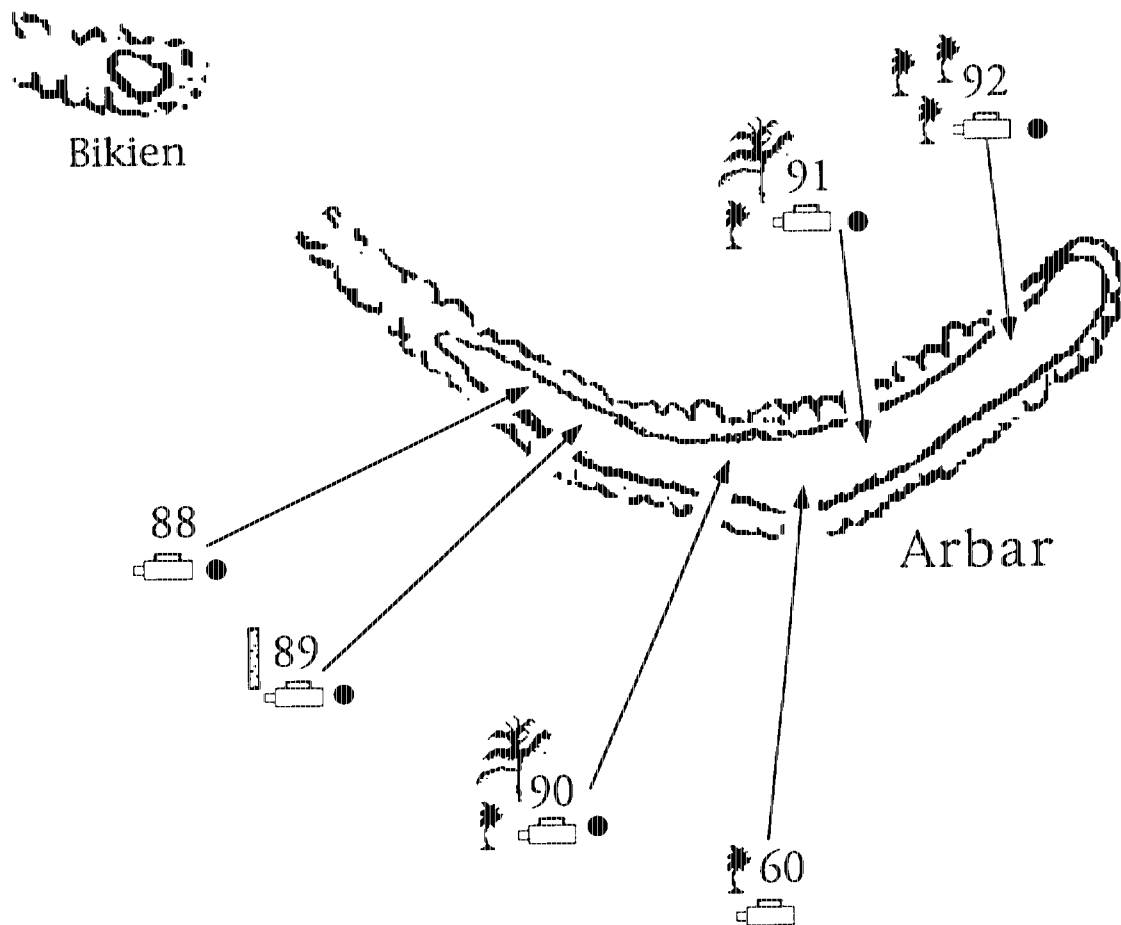
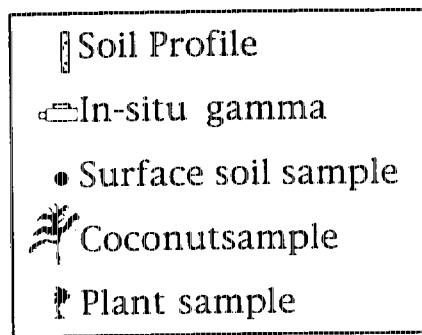
RONGELAP 6
(200 m x 200 m sampling grid)



RONGELAP Map 16
(200 x 200 m sampling grid)



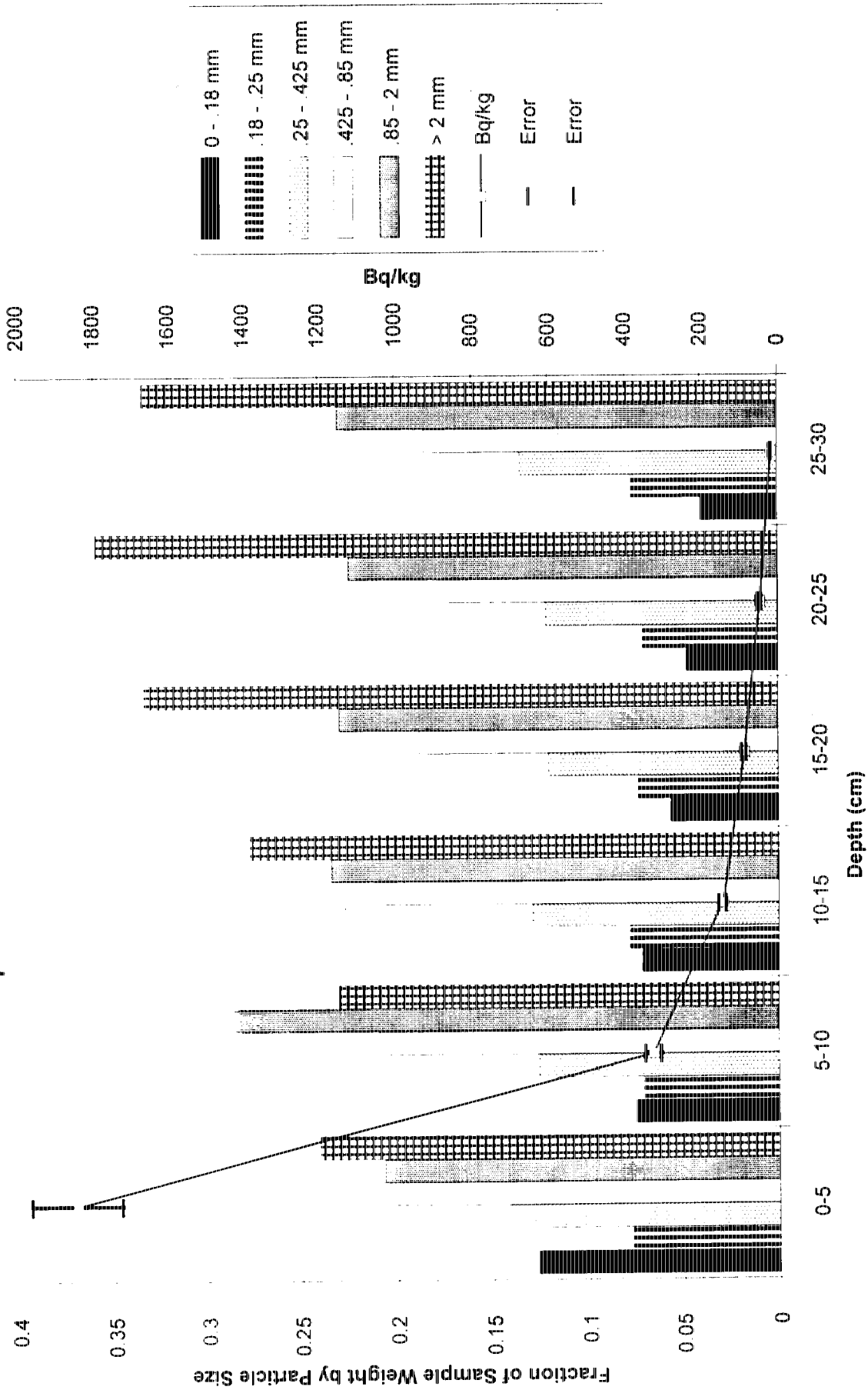
Rongelap Map 17
(200 x 200 m sampling plan)



RONGELAP Map 18
(200 m x 200 m sampling grid)

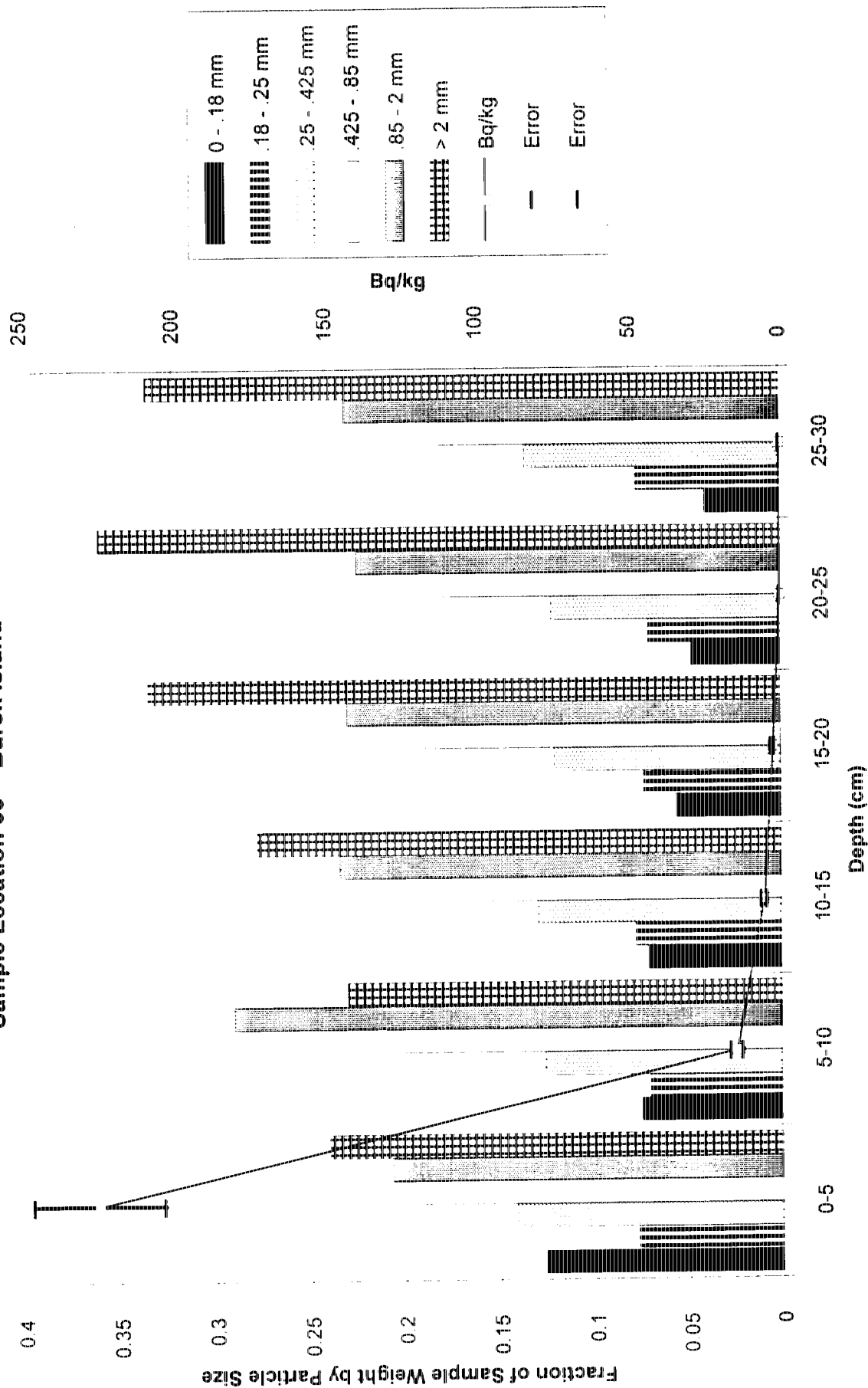
Rongelap Soil Profile 26s131 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 66 - Burok Island



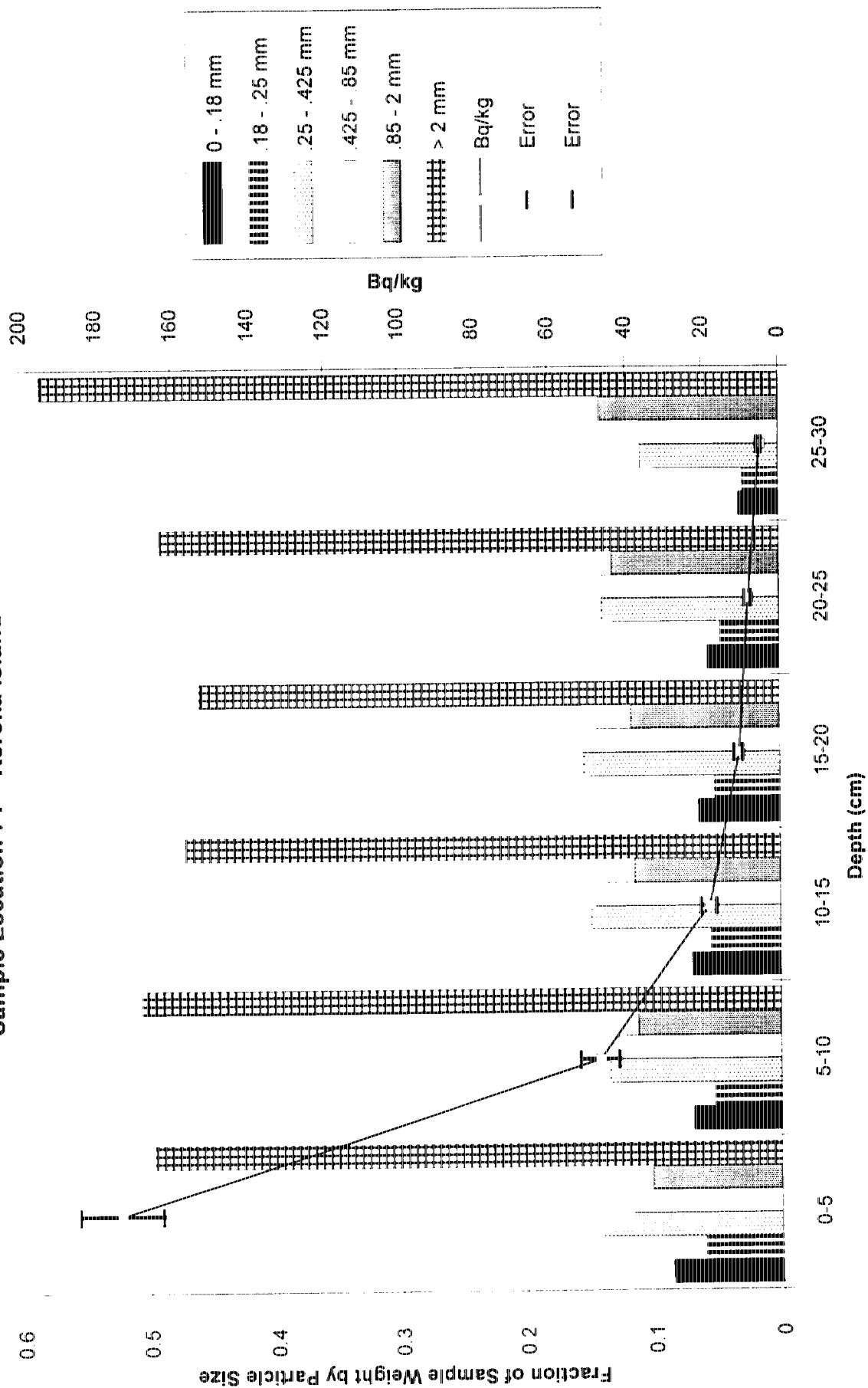
Rongelap Soil Profile 26s131 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 66 - Burok Island



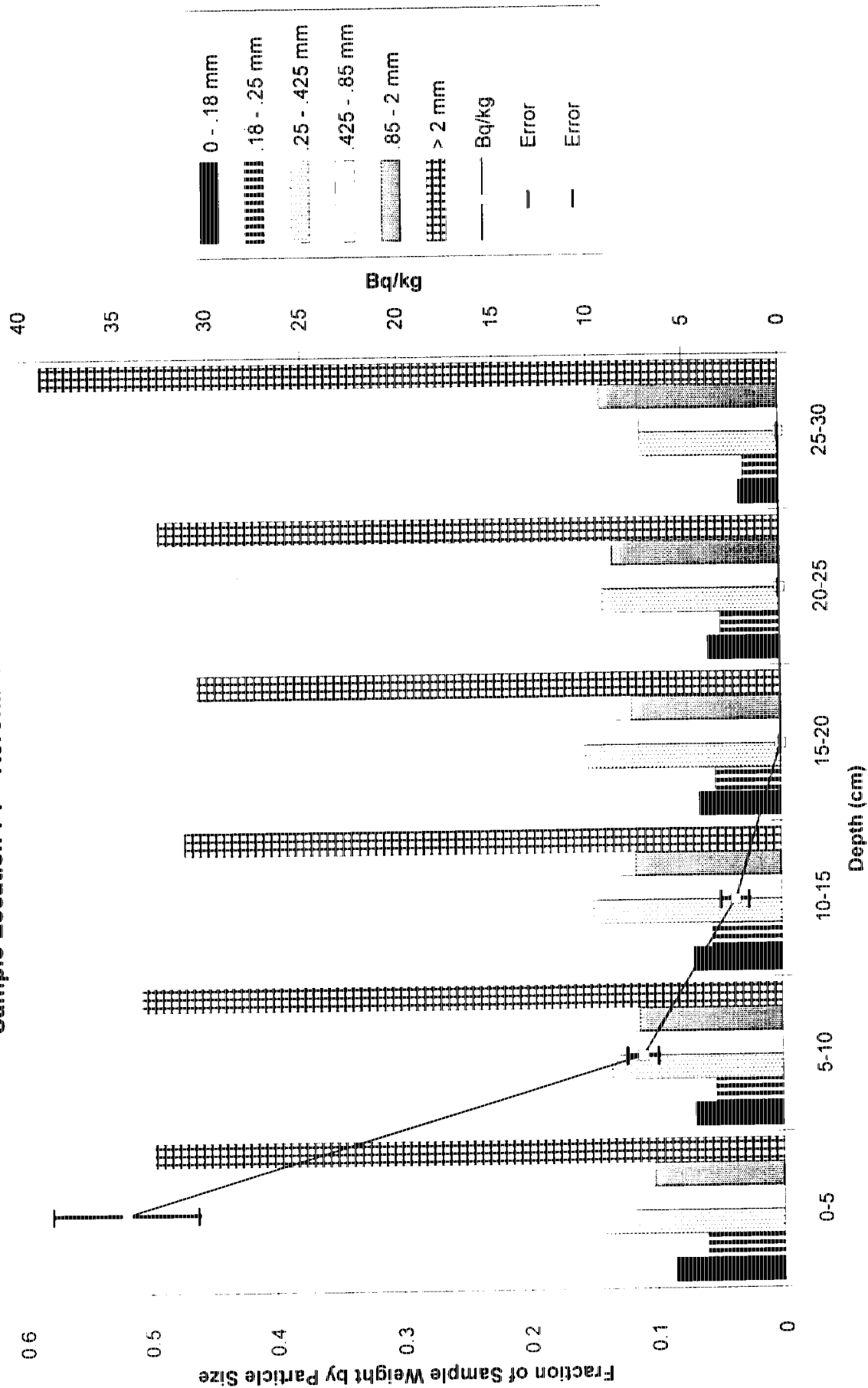
Rongelap Soil Profile 26s140 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 74 - Keroka Island



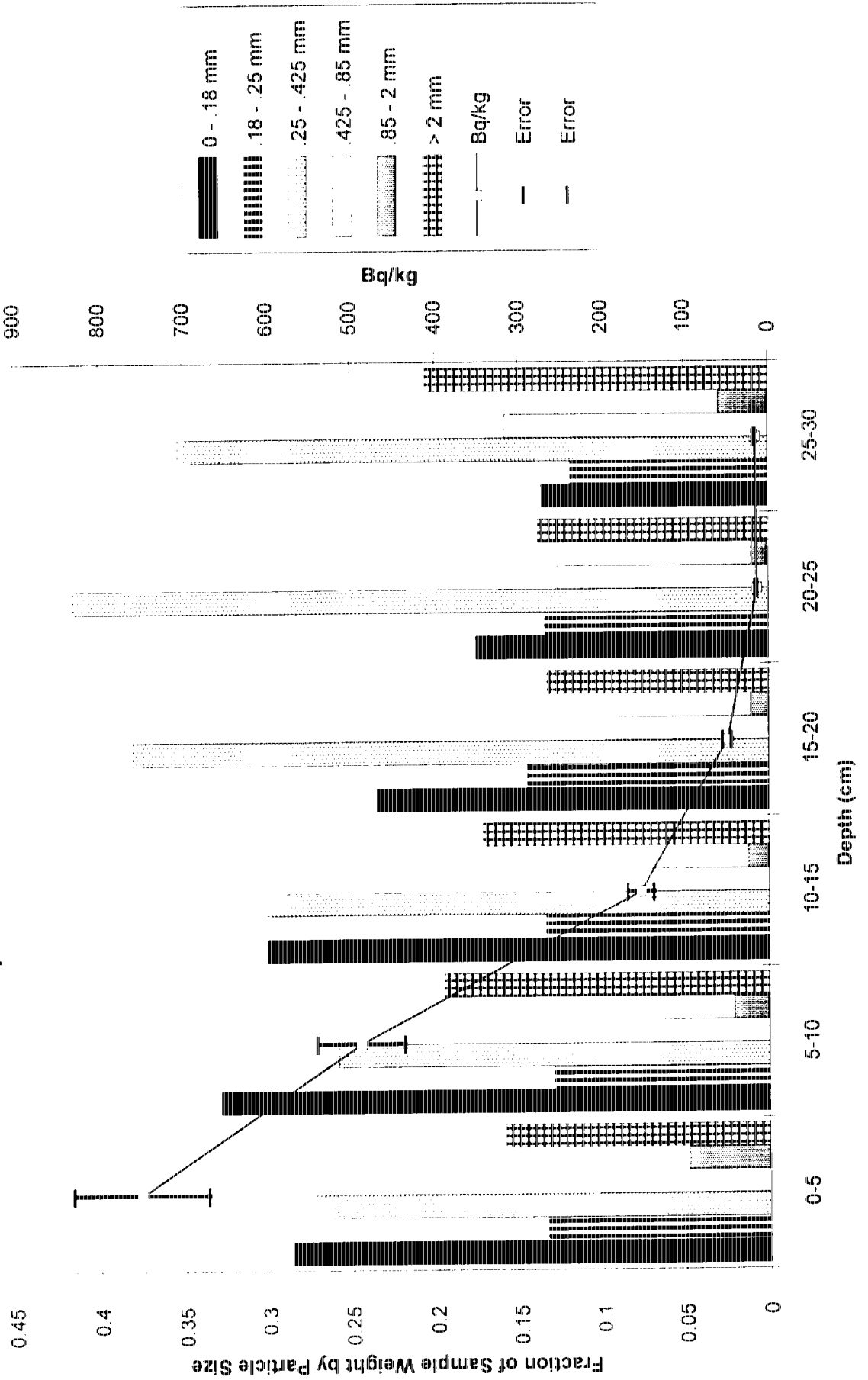
Rongelap Soil Profile 26s140 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 74 - Keroka Island



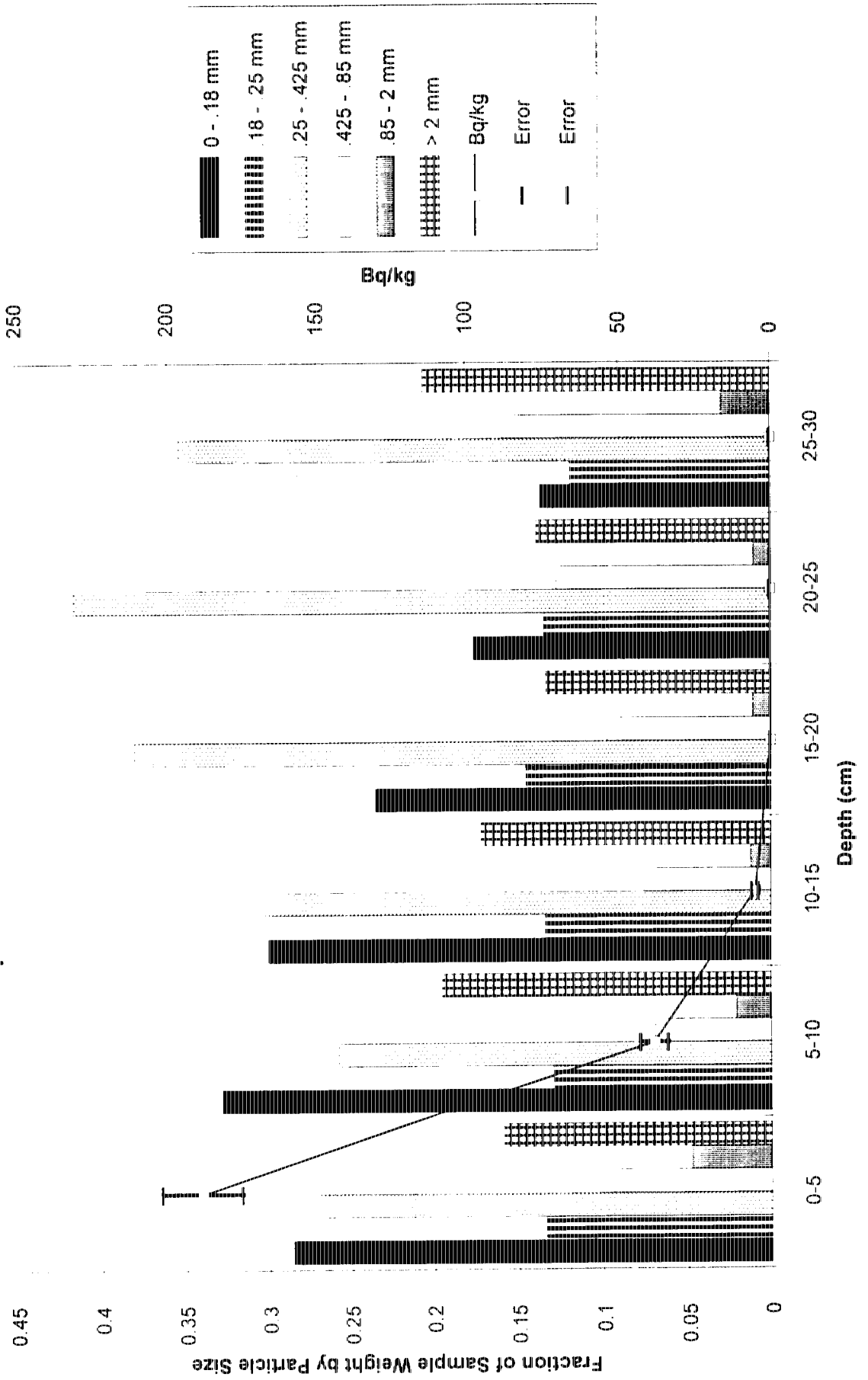
Rongelap Soil Profile 26s03 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 75 - Keroka Island



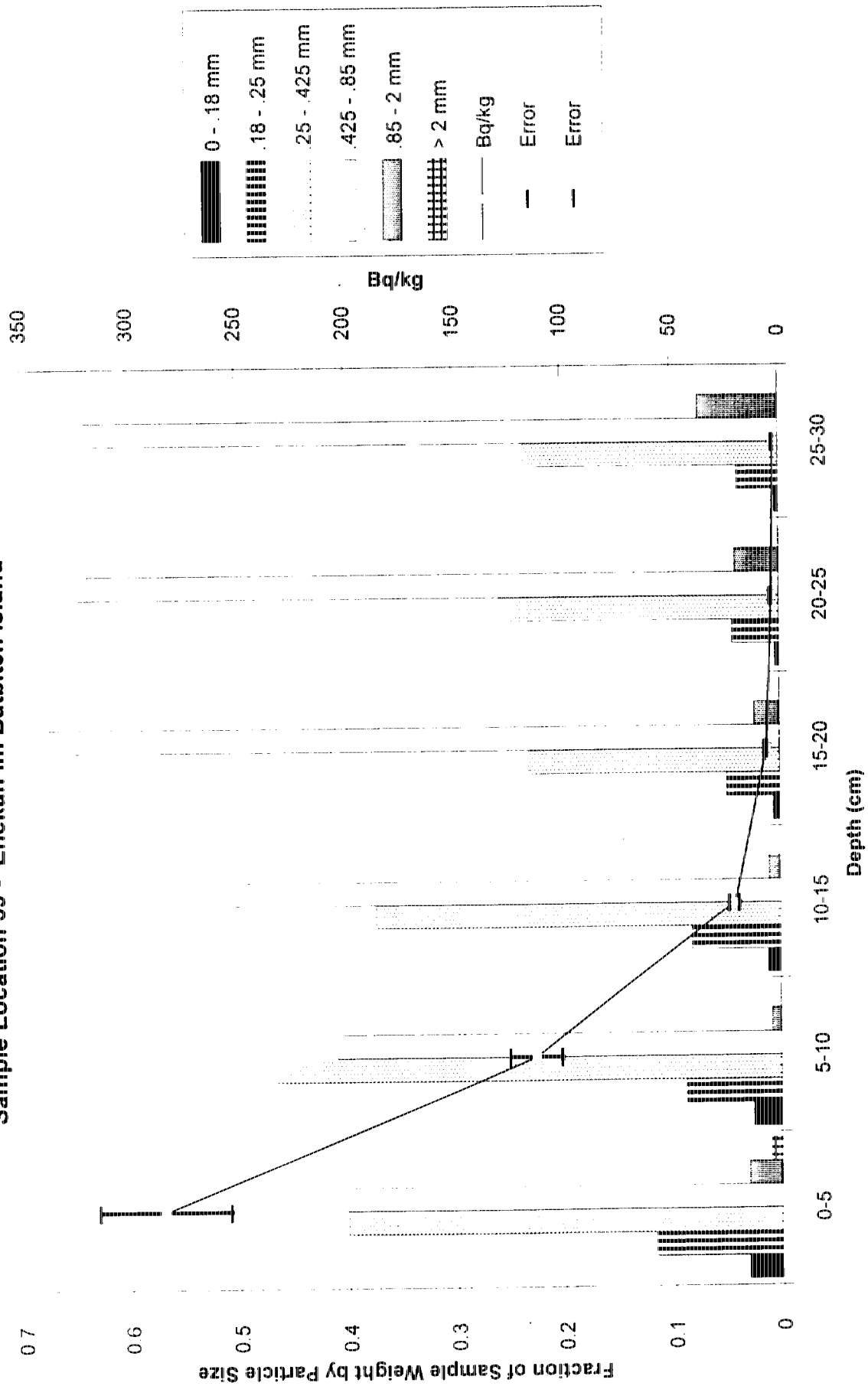
Rongelap Soil Profile 26s03 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 75 - Keroka Island



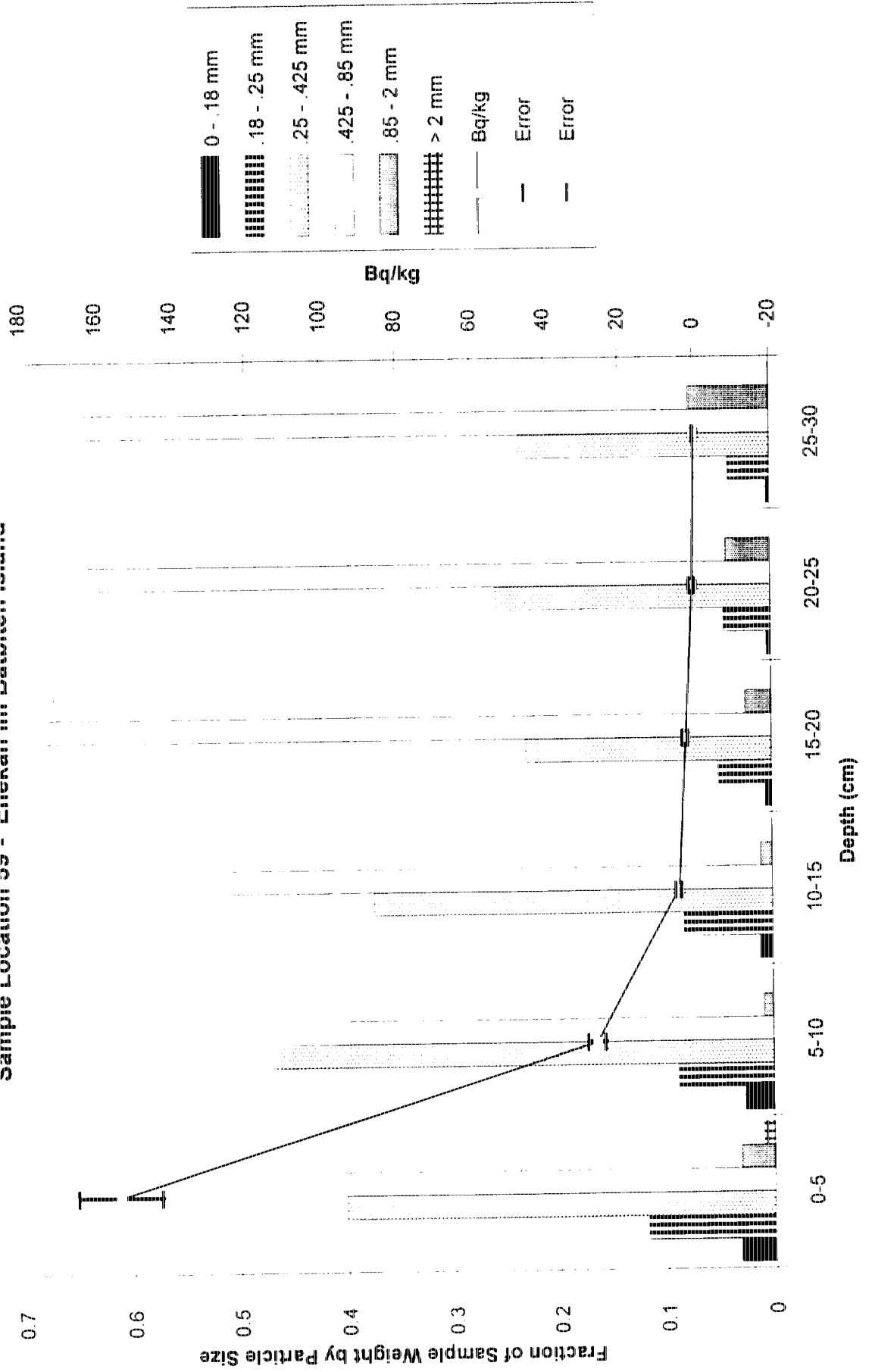
Rongelap Soil Profile 26s02 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 59 - Enekan im Batbiten Island



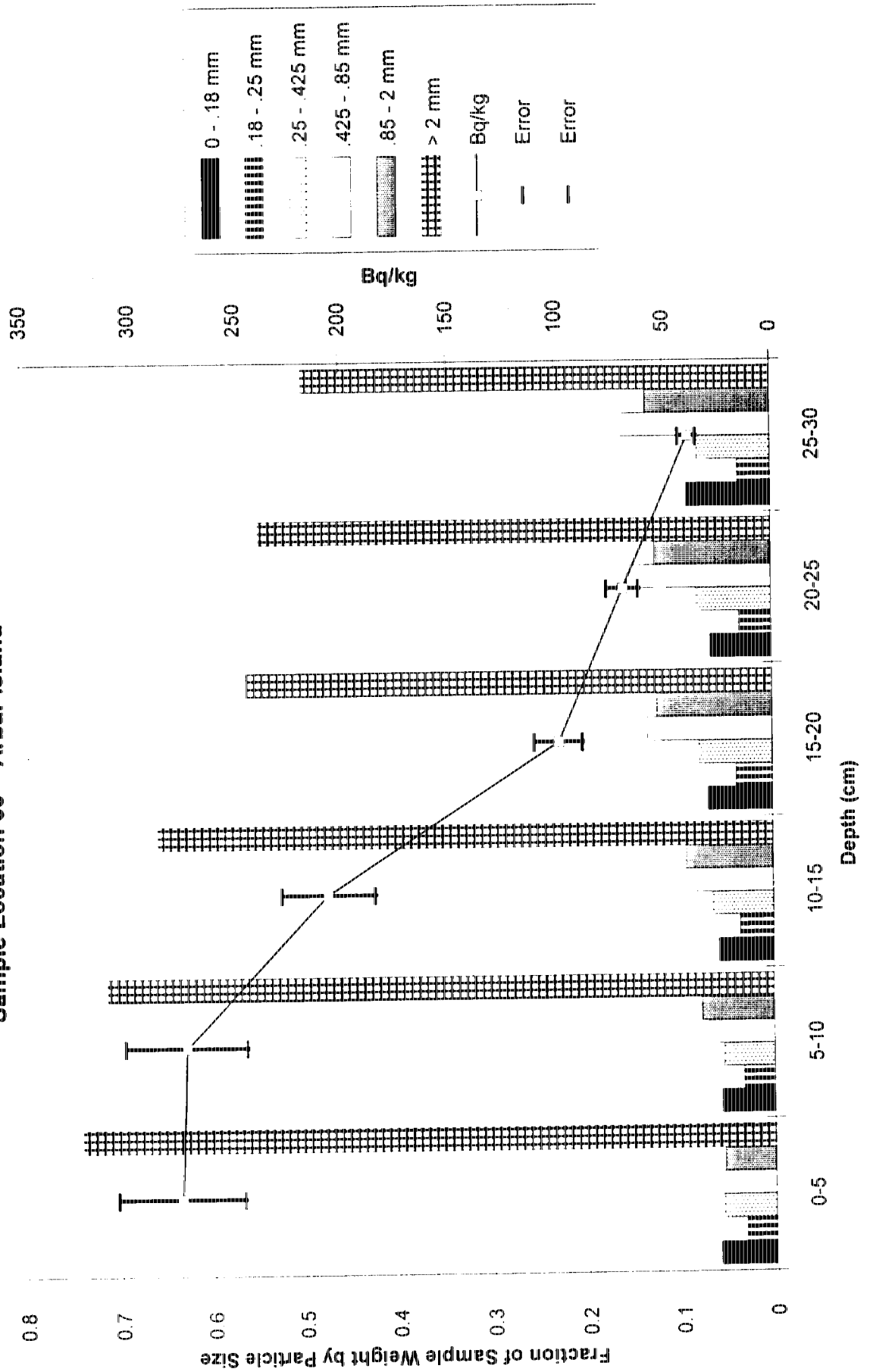
Rongelap Soil Profile 26s02 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 59 - Enekan im Batbiten Island



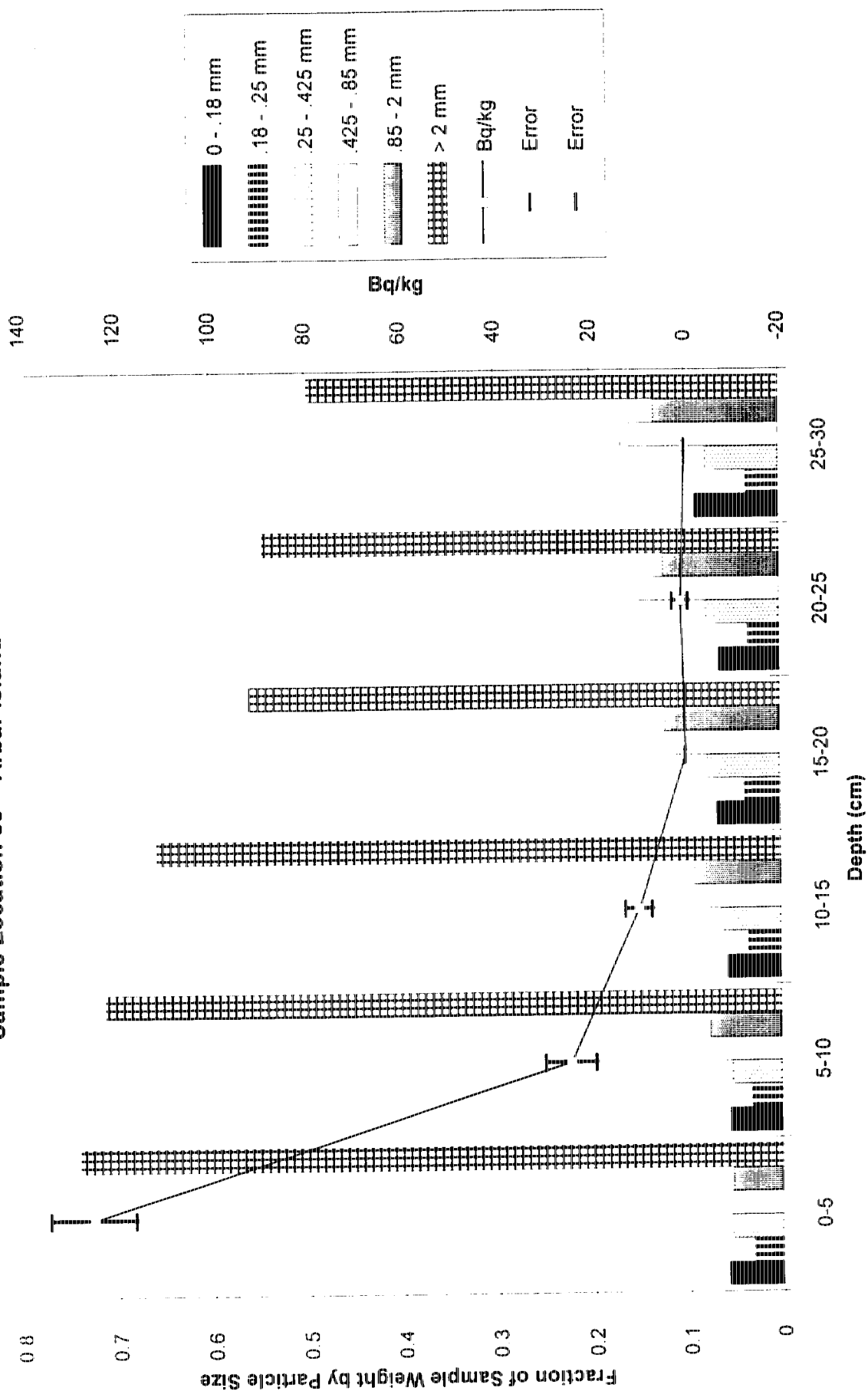
Rongelap Soil Profile 26s09 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 60 - Arbar Island



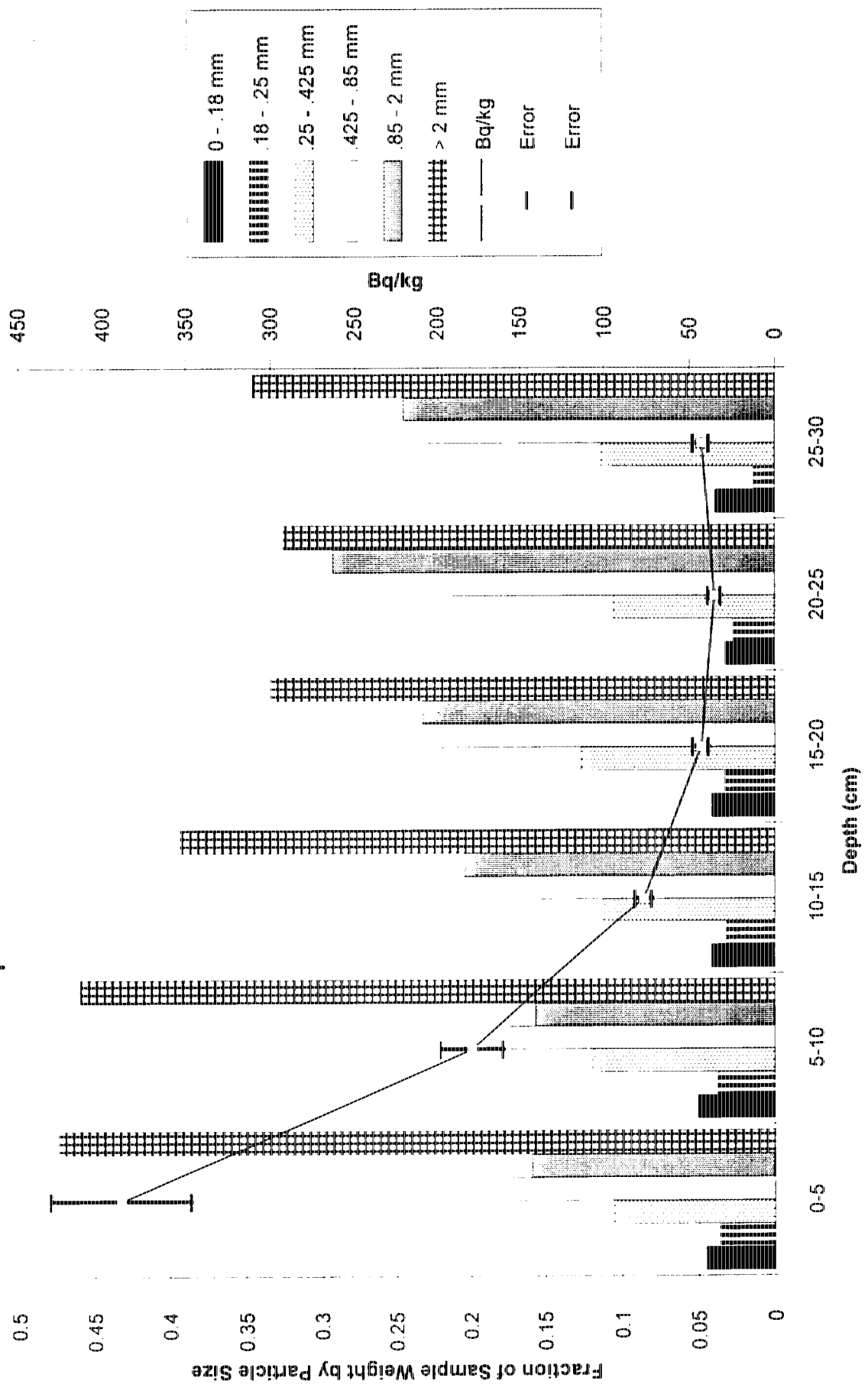
Rongelap Soil Profile 26s09 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 60 - Arbar Island



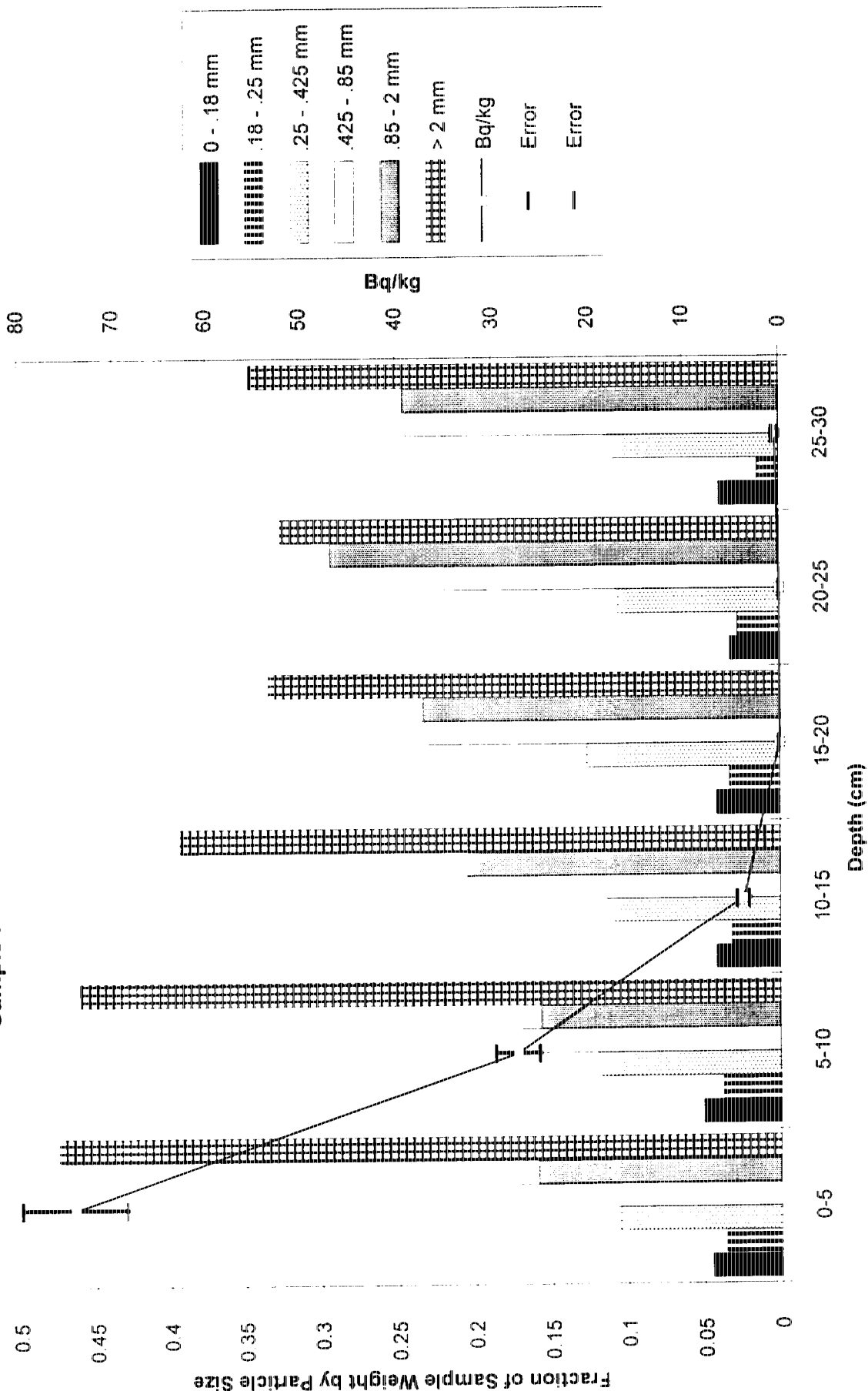
Rongelap Soil Profile 26s10 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 89 - Arbar Island



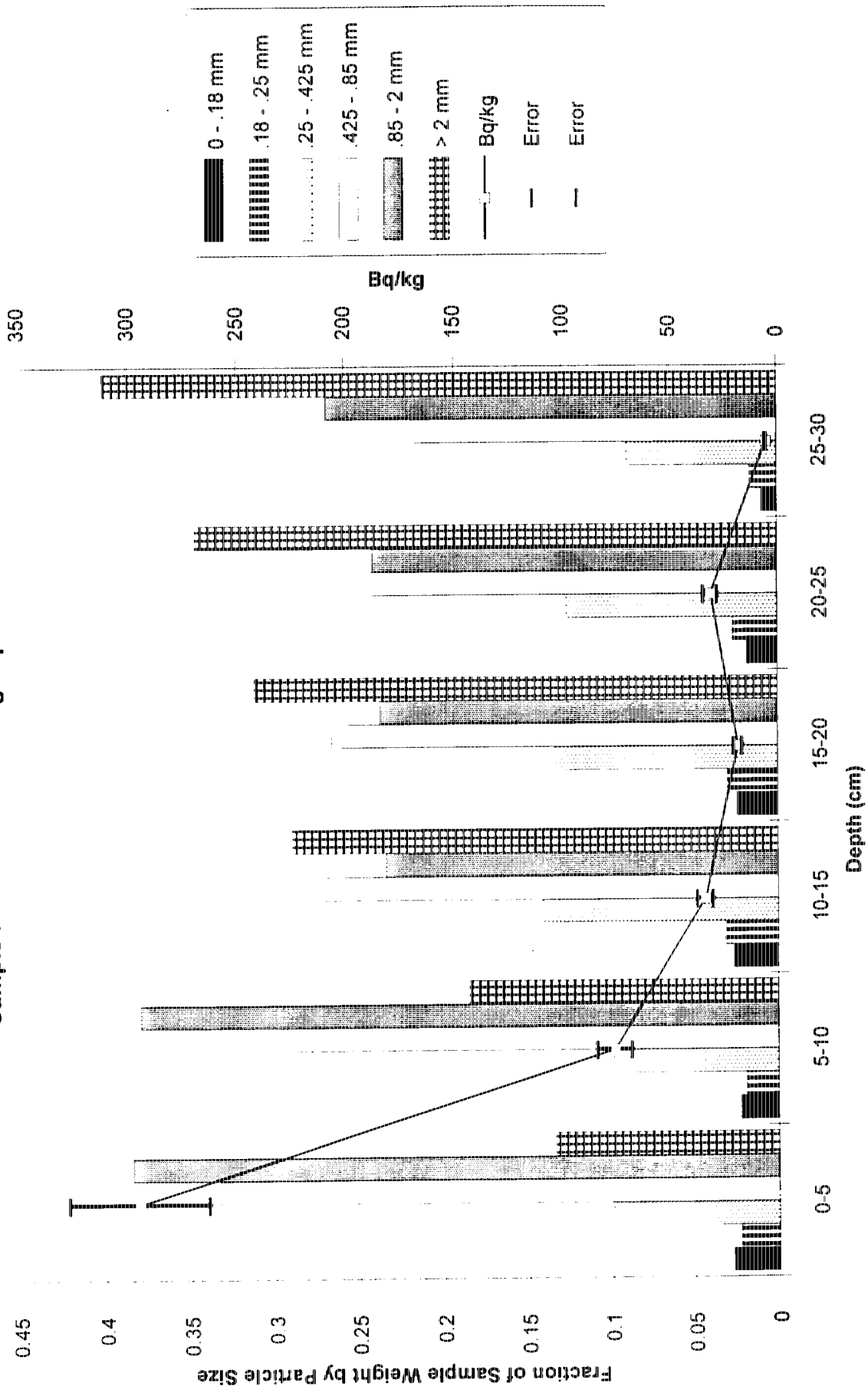
Rongelap Soil Profile 26s10 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 89 - Arbar Island

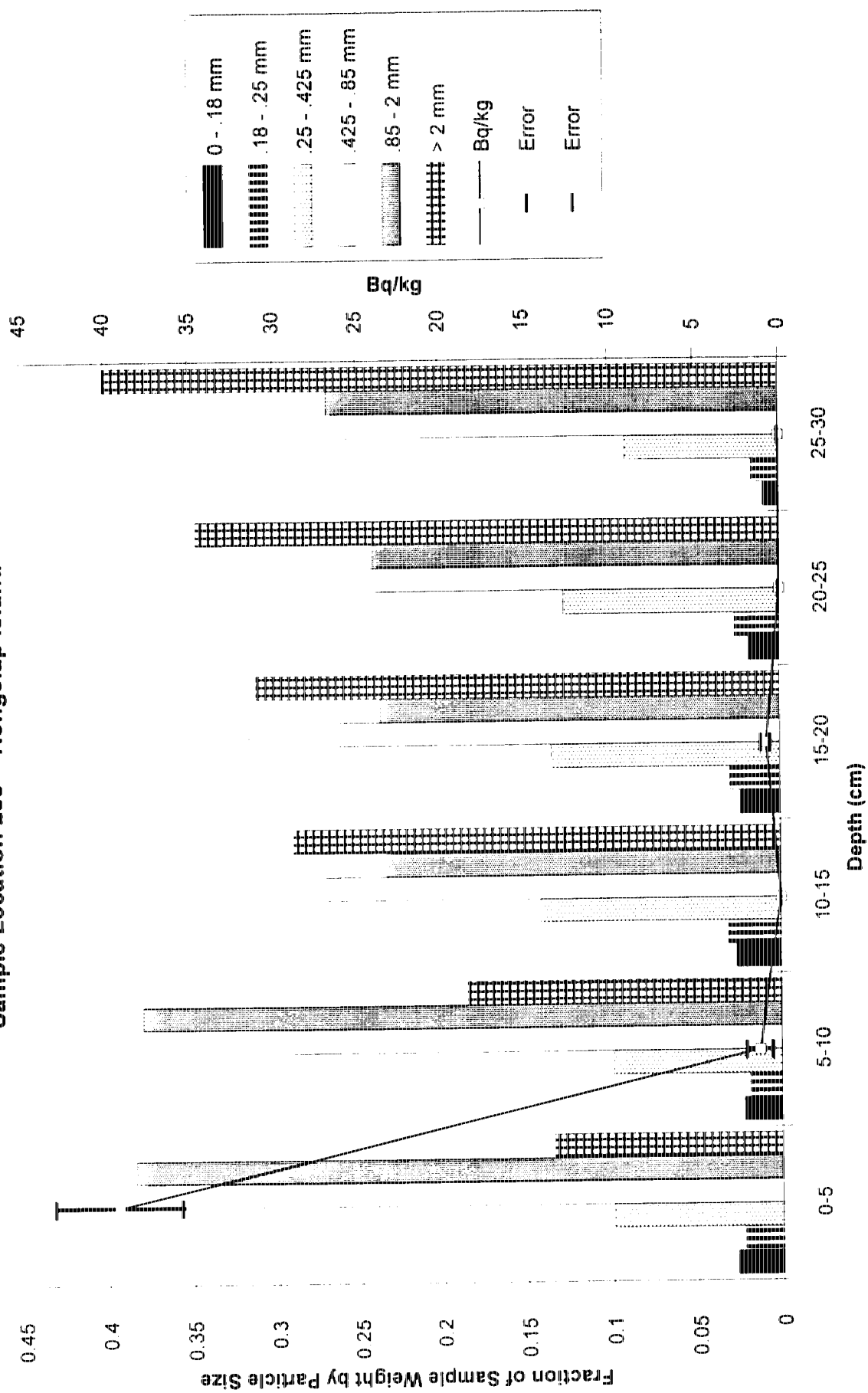


Rongelap Soil Profile 26s81 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 239 - Rongelap Island

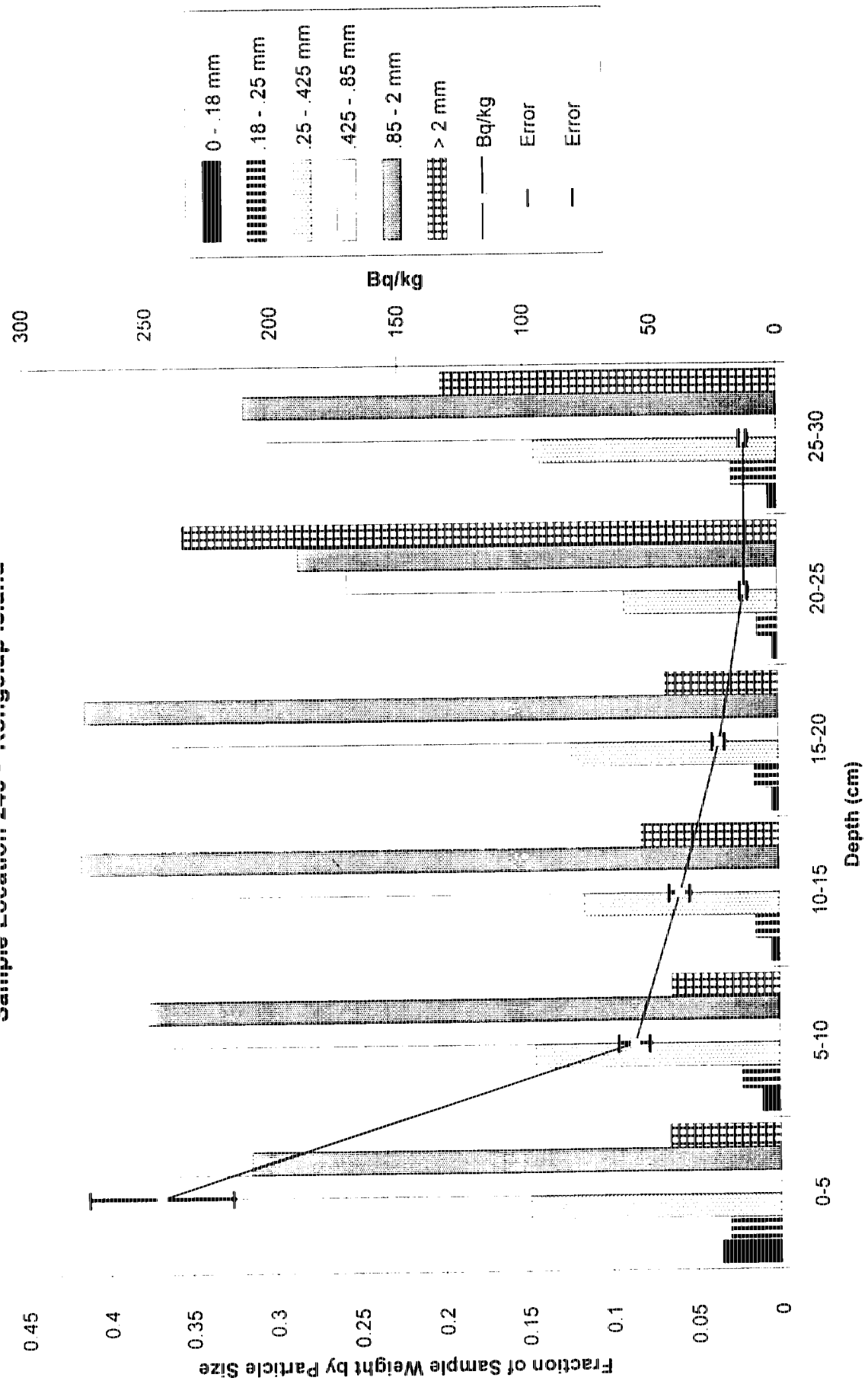


Sample Location 239 - Rongelap Island



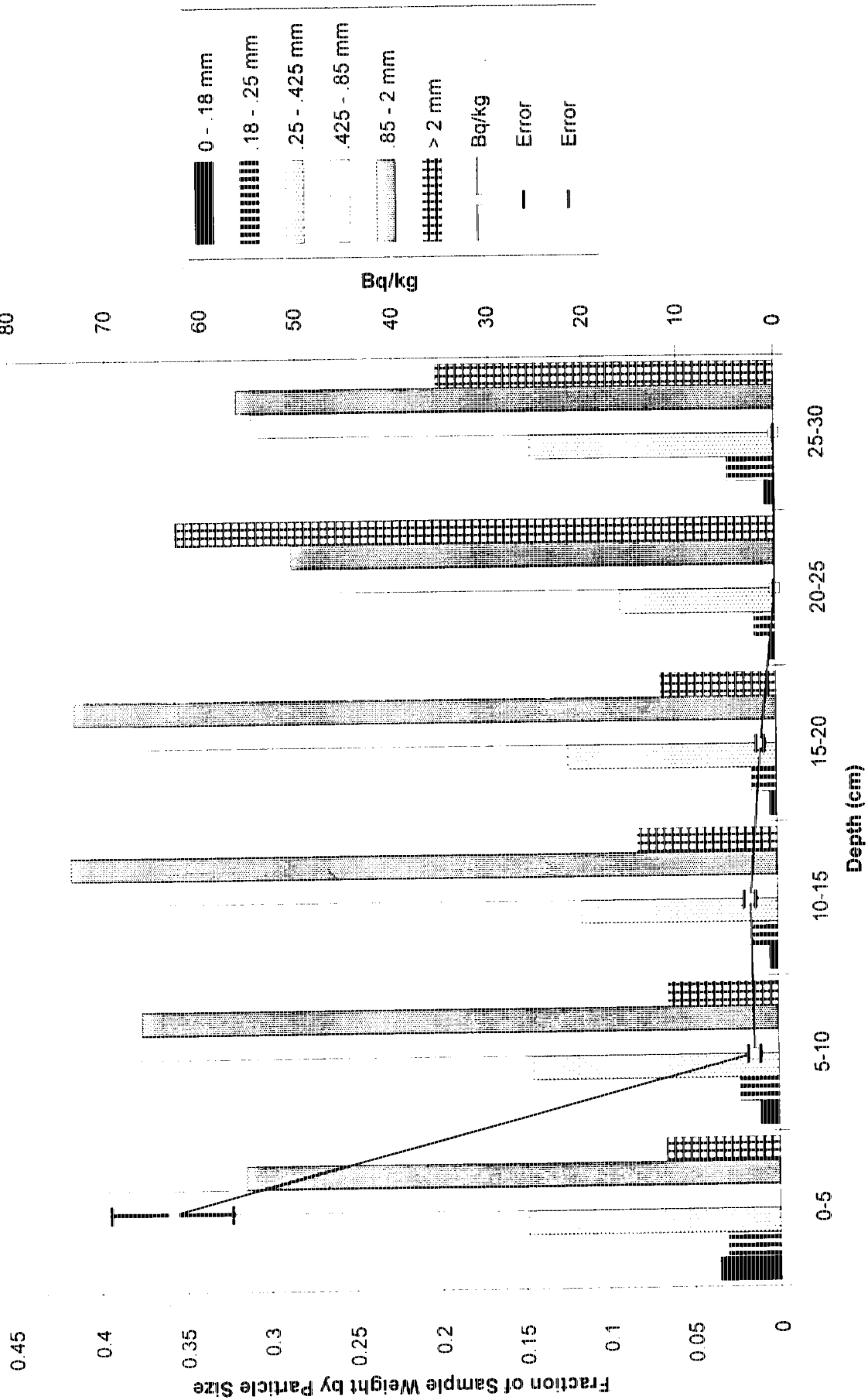
Rongelap Soil Profile 26s12 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 240 - Rongelap Island



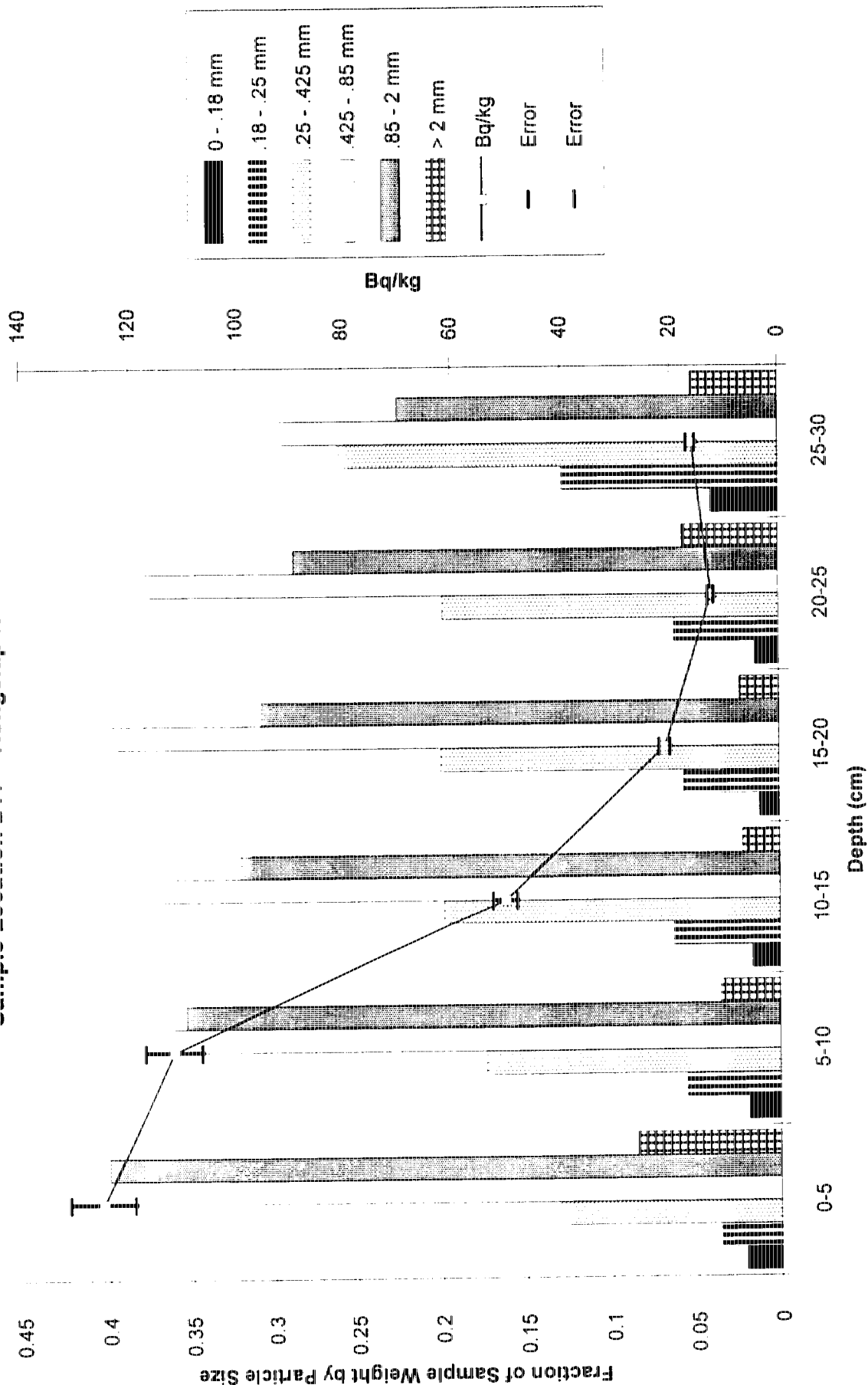
Rongelap Soil Profile 26s12 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 240 - Rongelap Island



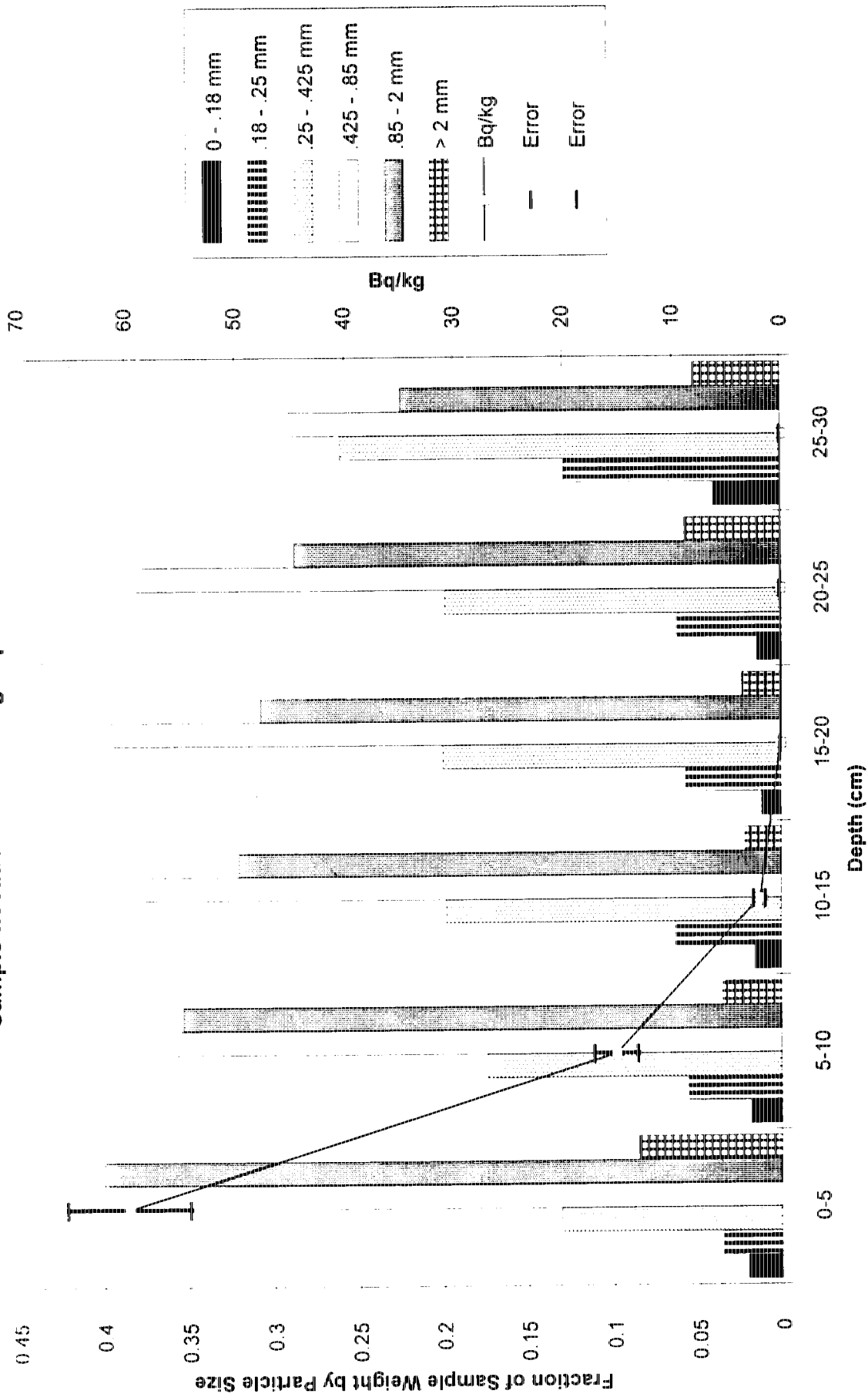
Rongelap Soil Profile 26s82 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 241 - Rongelap Island



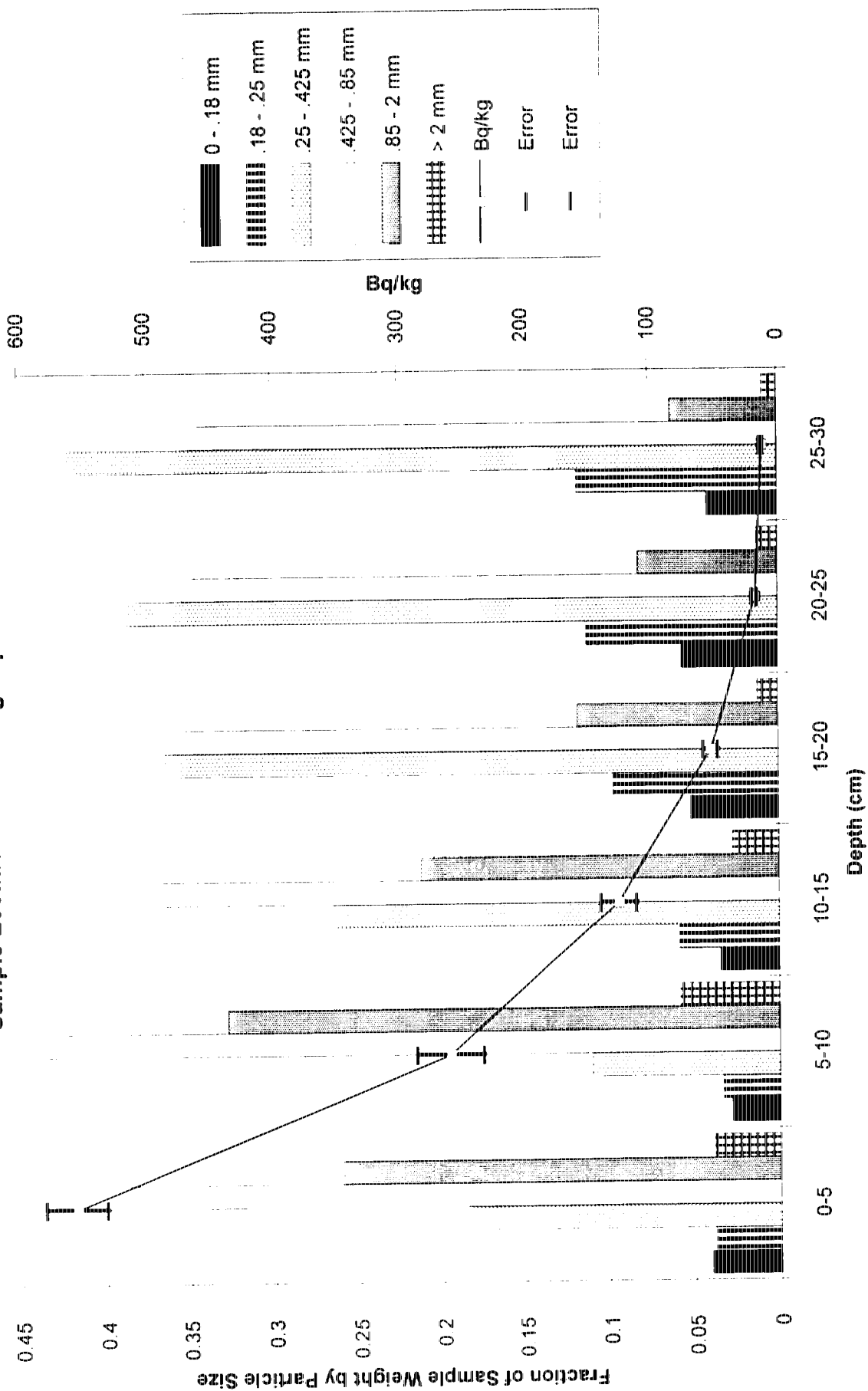
Rongelap Soil Profile 26s82 **Particle Size Distribution and Americium (Bq/kg) with Depth**

Sample Location 241 - Rongelap Island

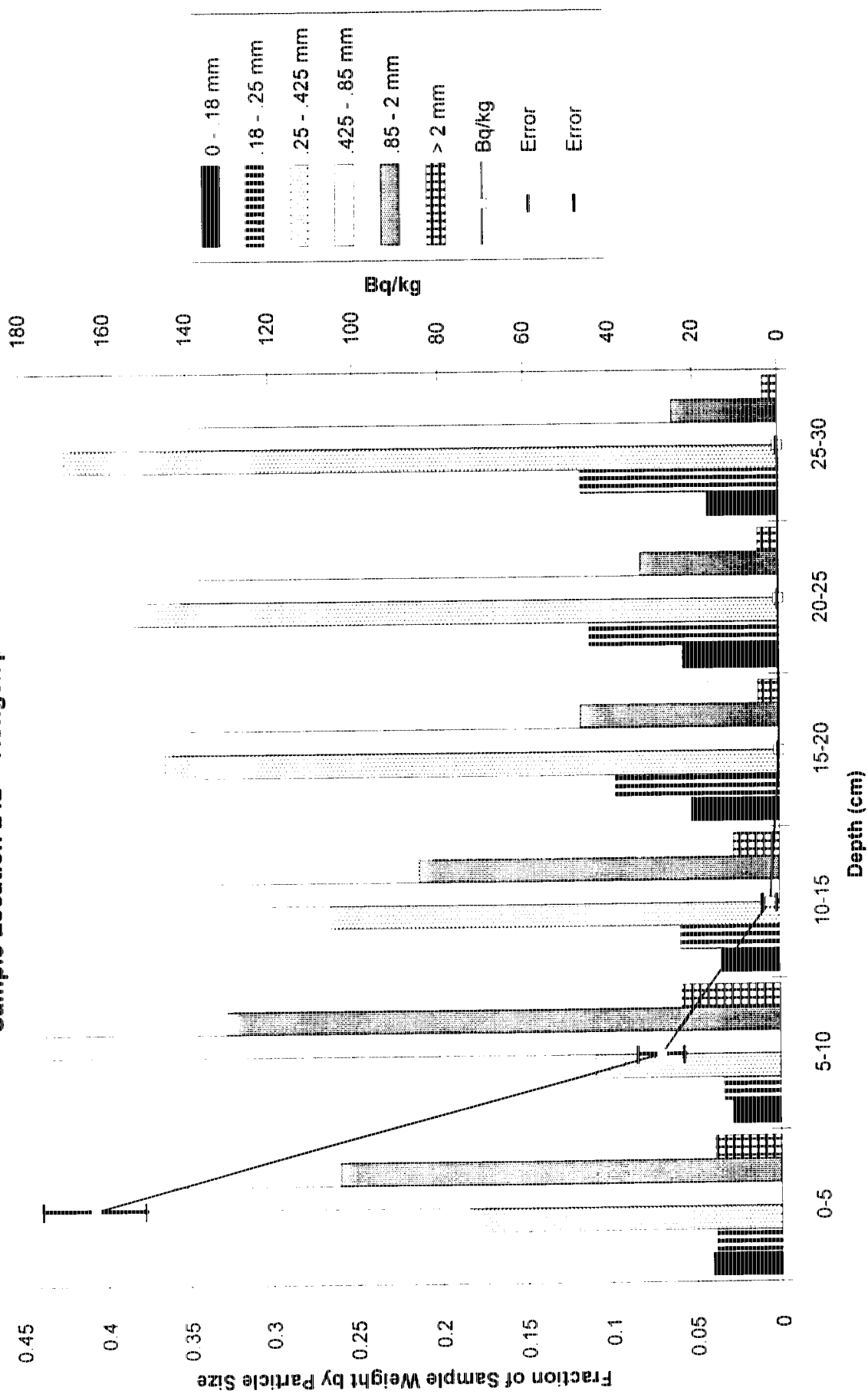


Rongelap Soil Profile 26s79 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 242 - Rongelap Island

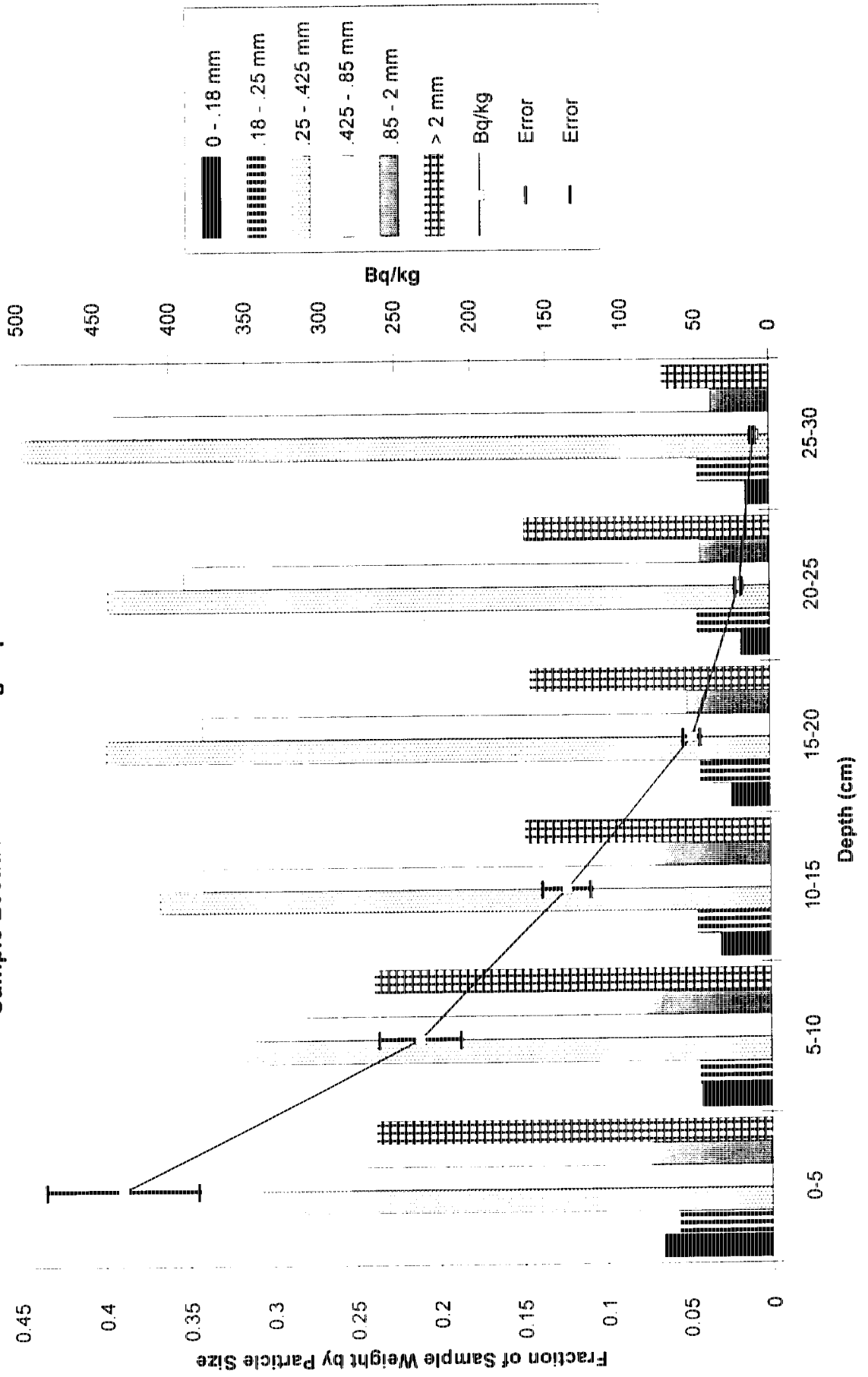


Sample Location 242 - Rongelap Island



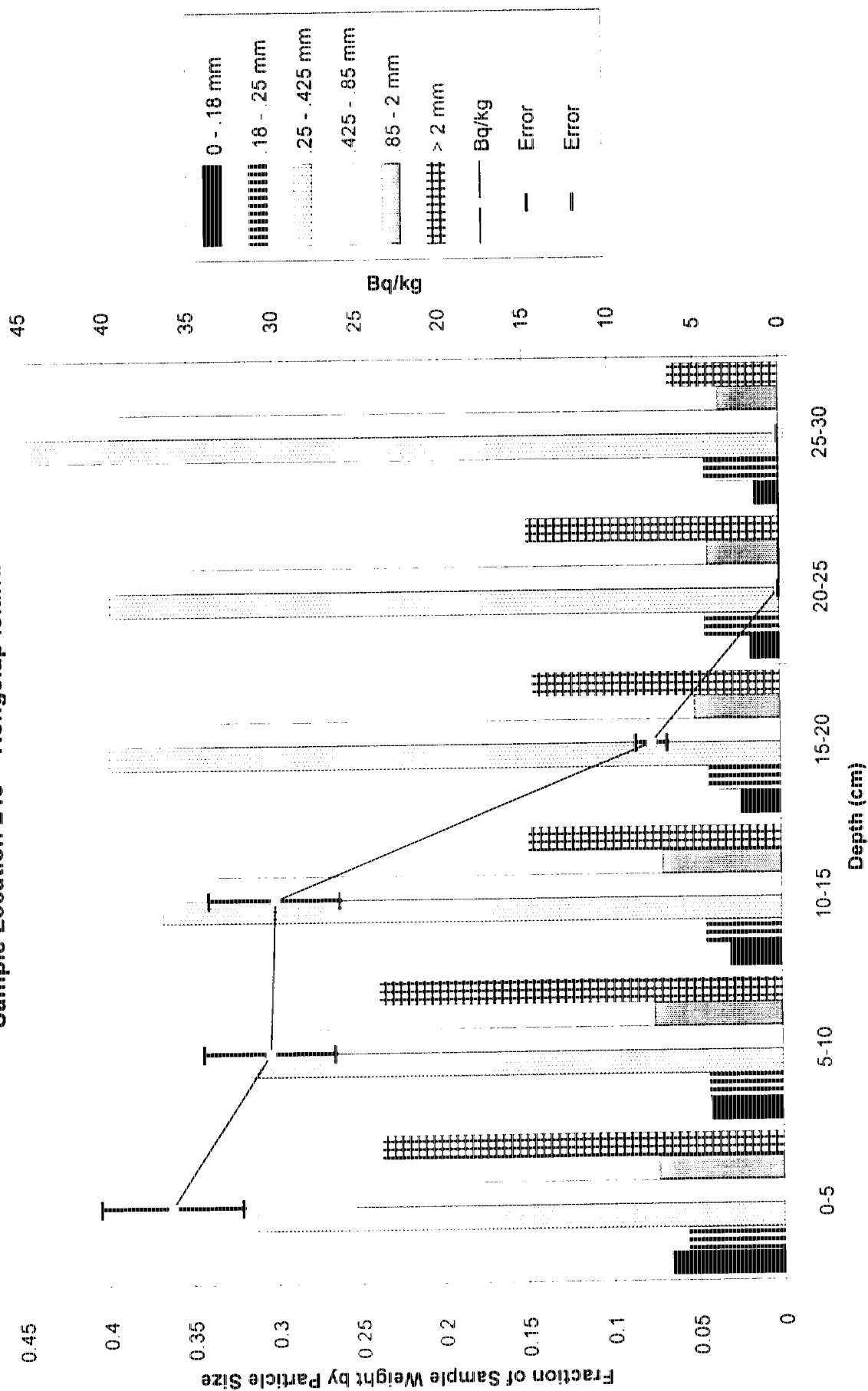
Rongelap Soil Profile 26s77 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 243 - Rongelap Island



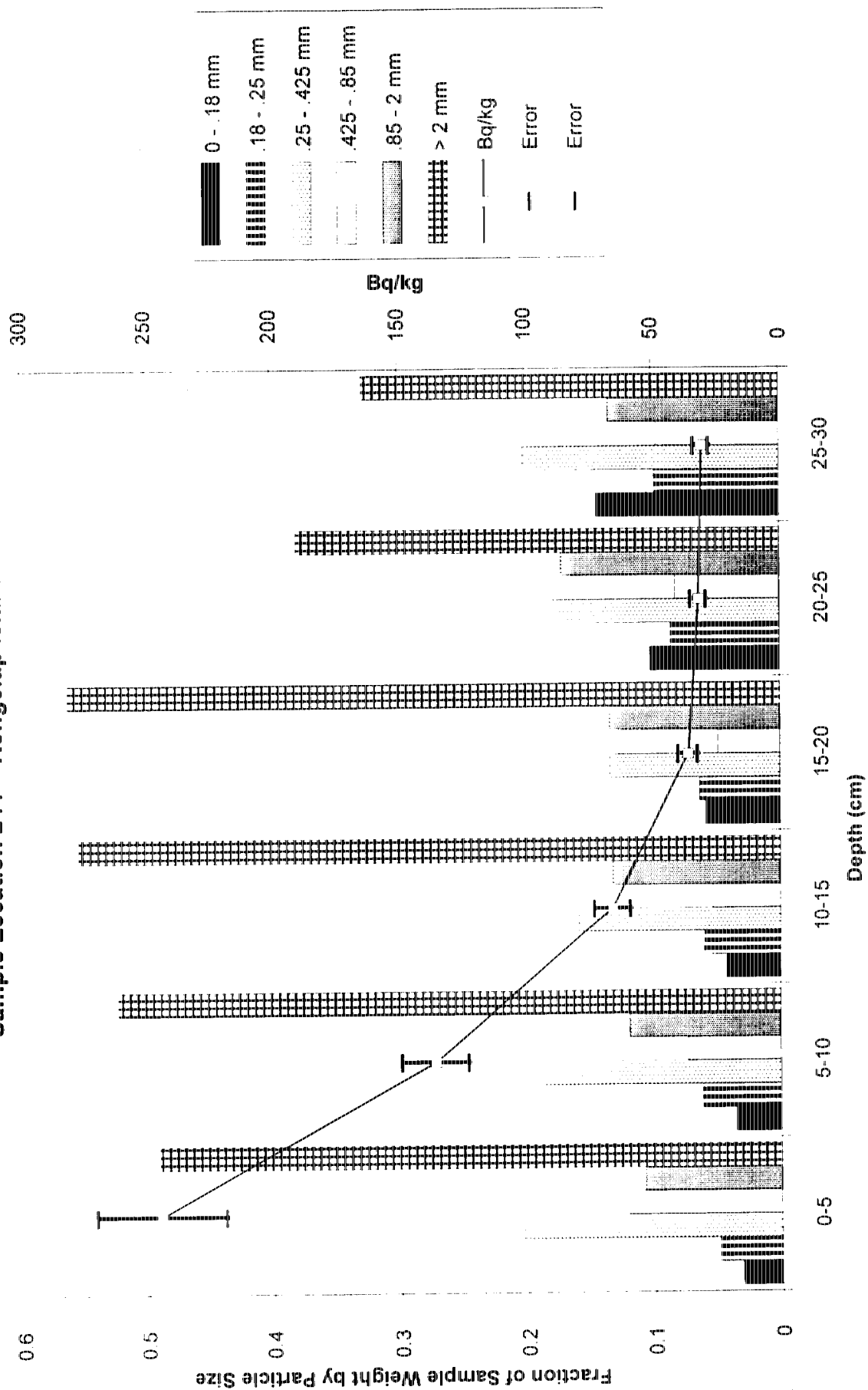
Rongelap Soil Profile 26s77

Sample Location 243 - Rongelap Island

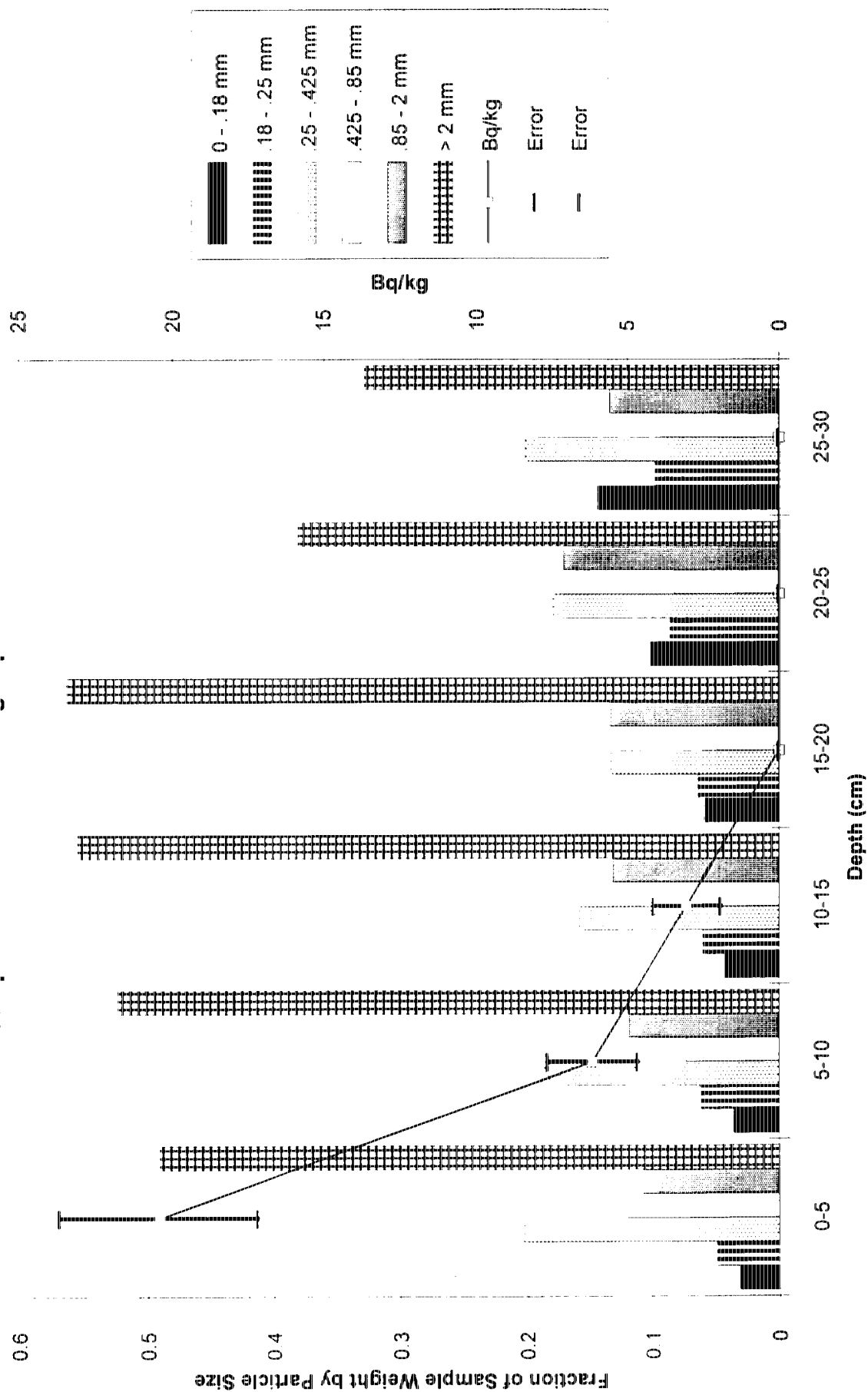


Rongelap Soil Profile 26s80 Particle Size Distribution and Cesium (Bq/kg) with Depth

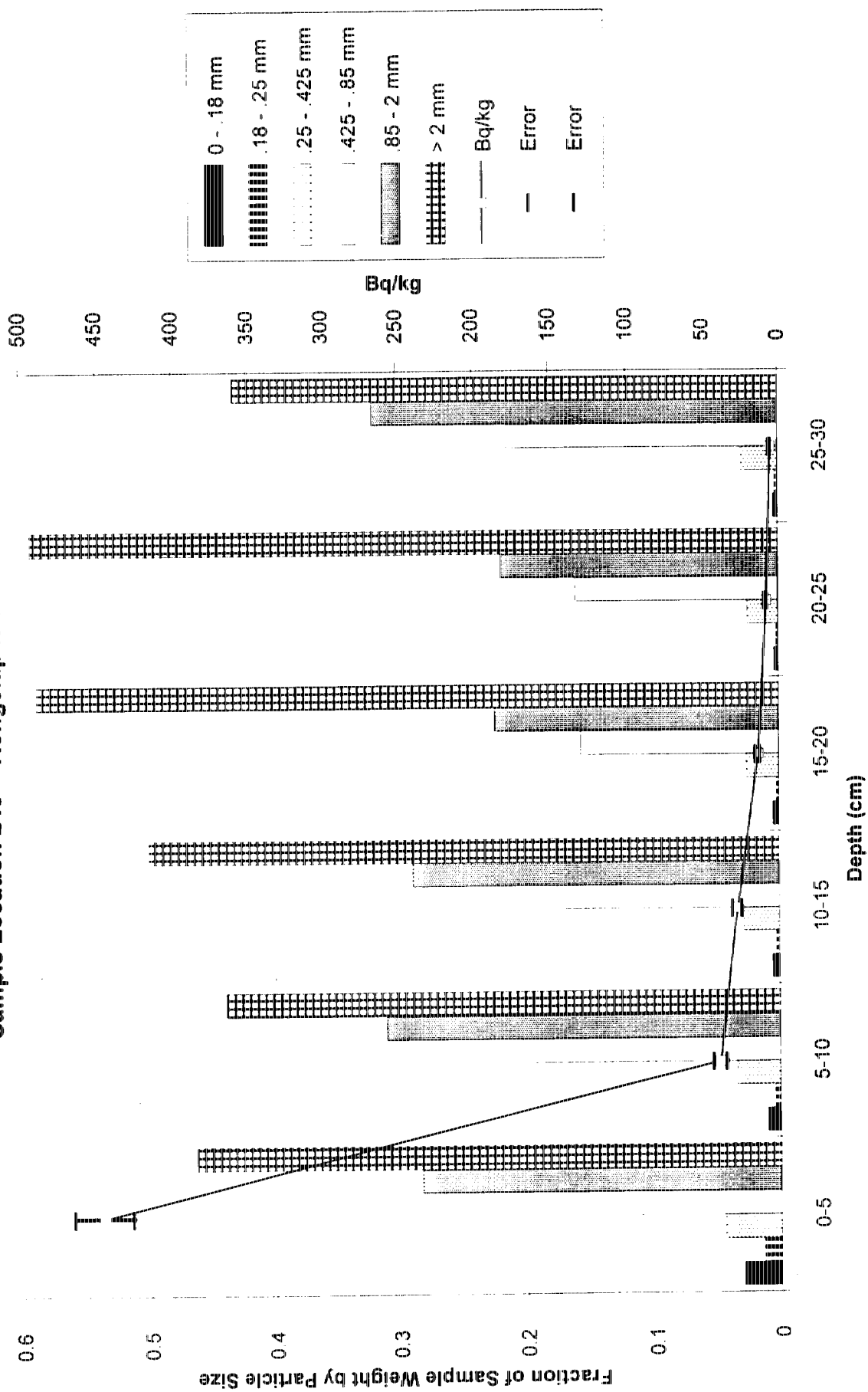
Sample Location 244 - Rongelap Island



Sample Location 244 - Rongelap Island

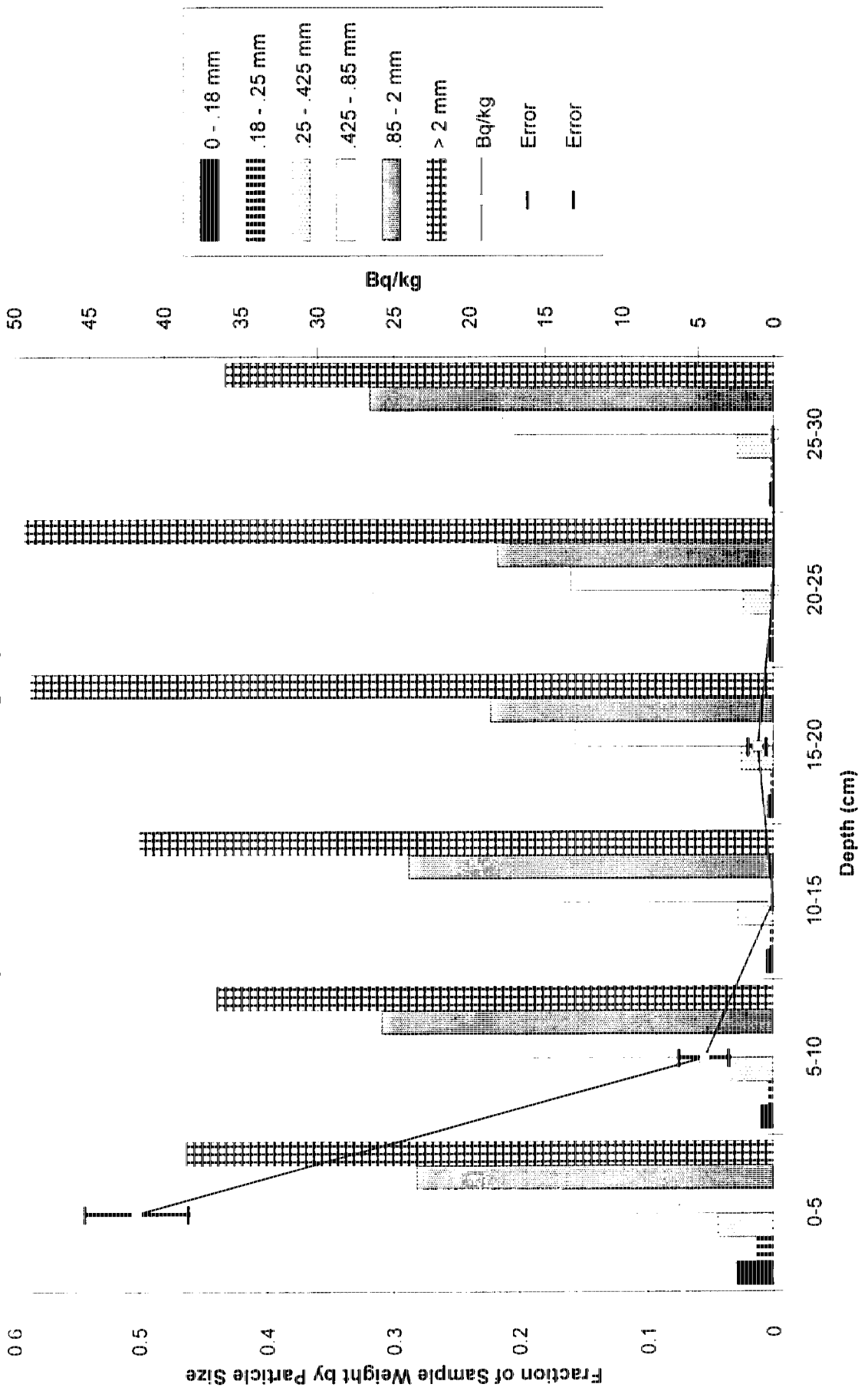


Sample Location 245 - Rongelap Island



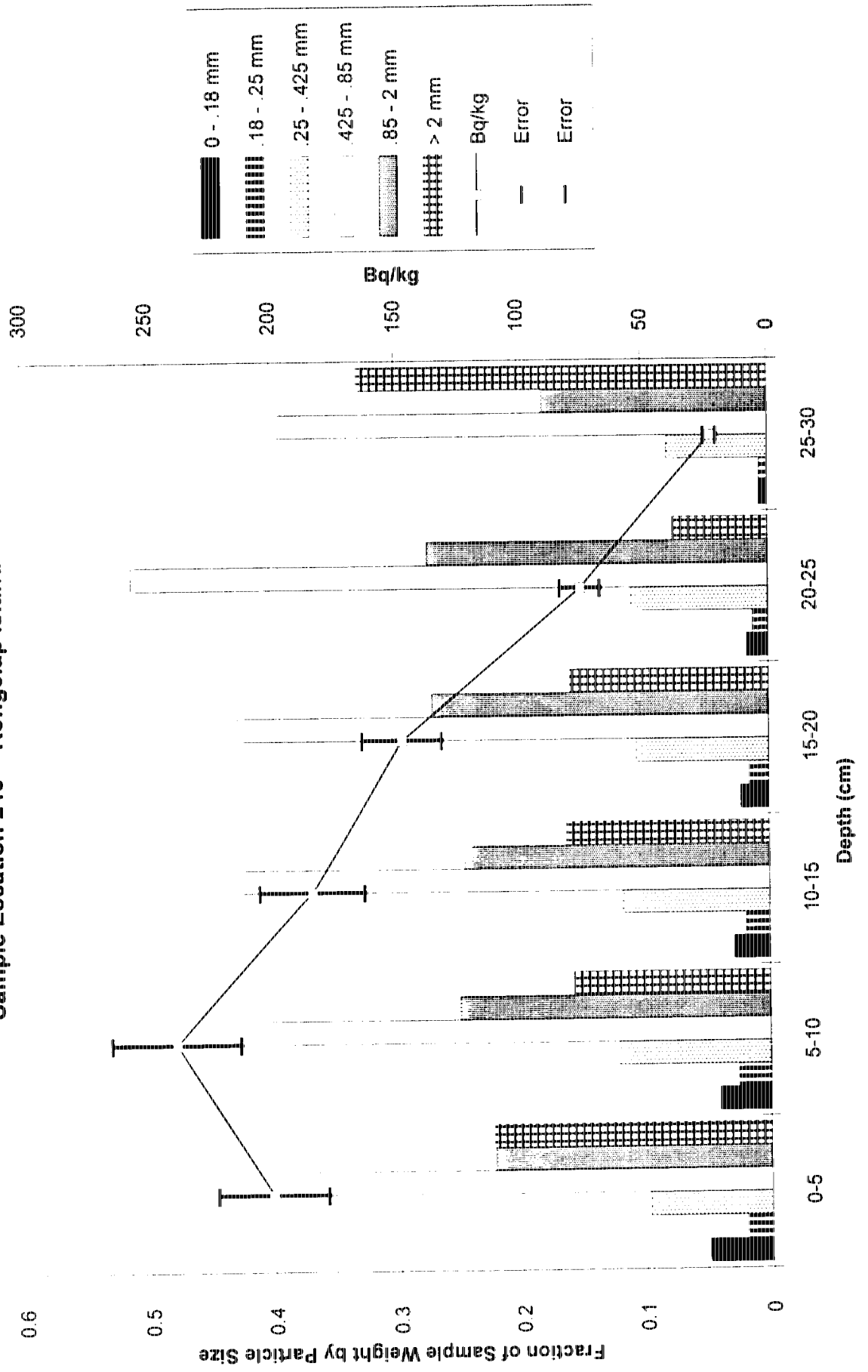
Rongelap Soil Profile 26s78 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 245 - Rongelap Island



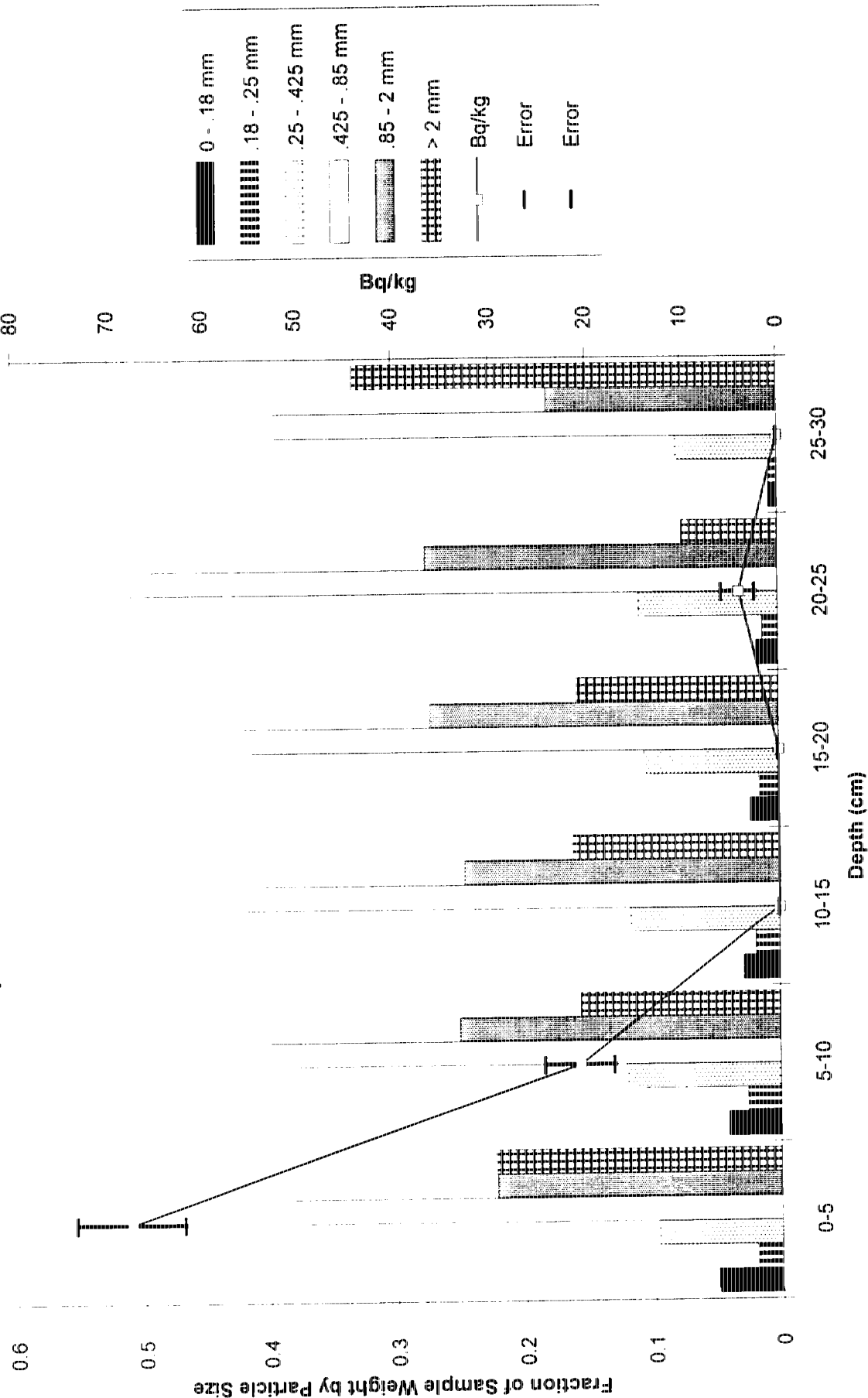
Rongelap Soil Profile 26s08 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 246 - Rongelap Island

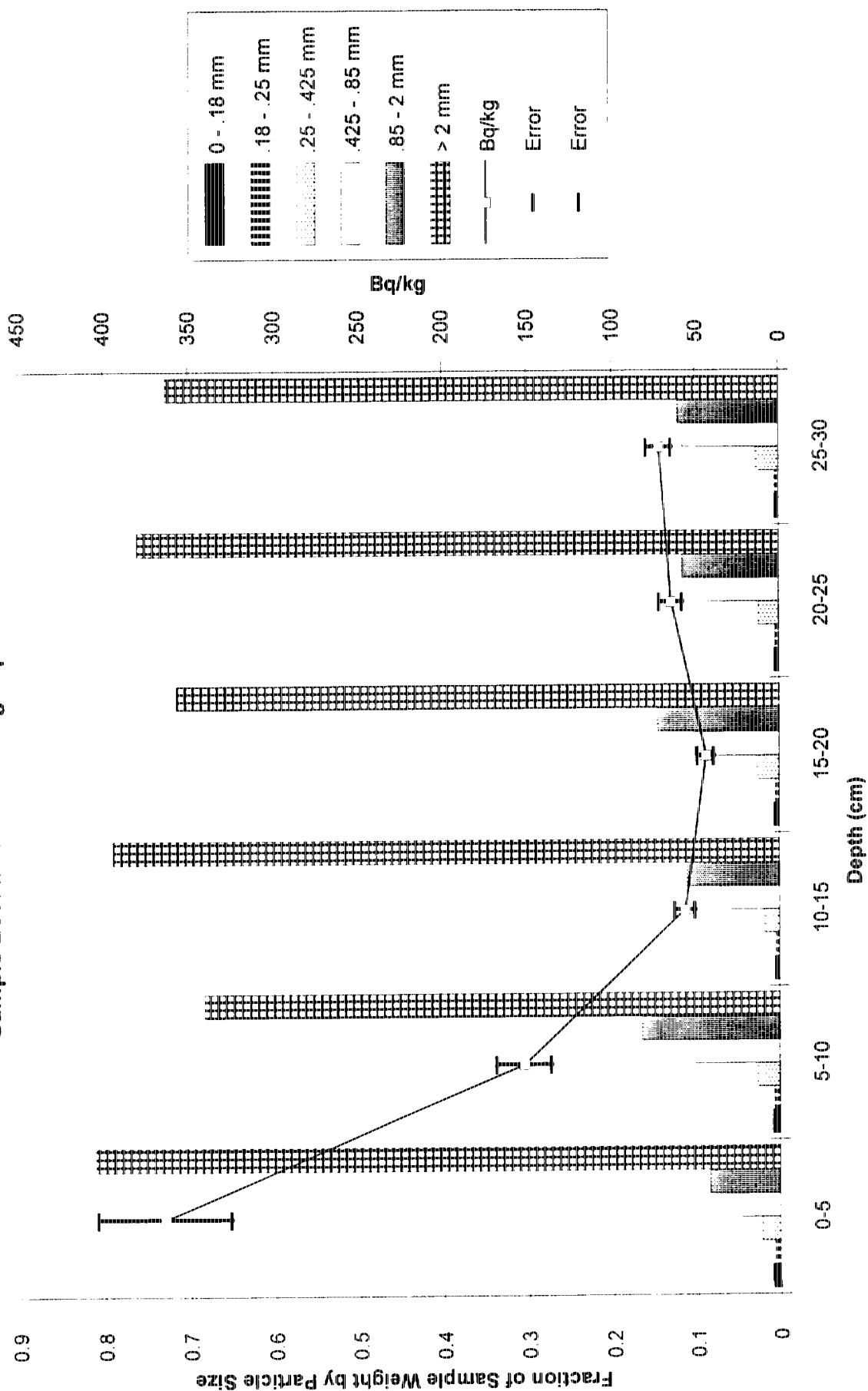


Rongelap Soil Profile 26s08 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 246 - Rongelap Island

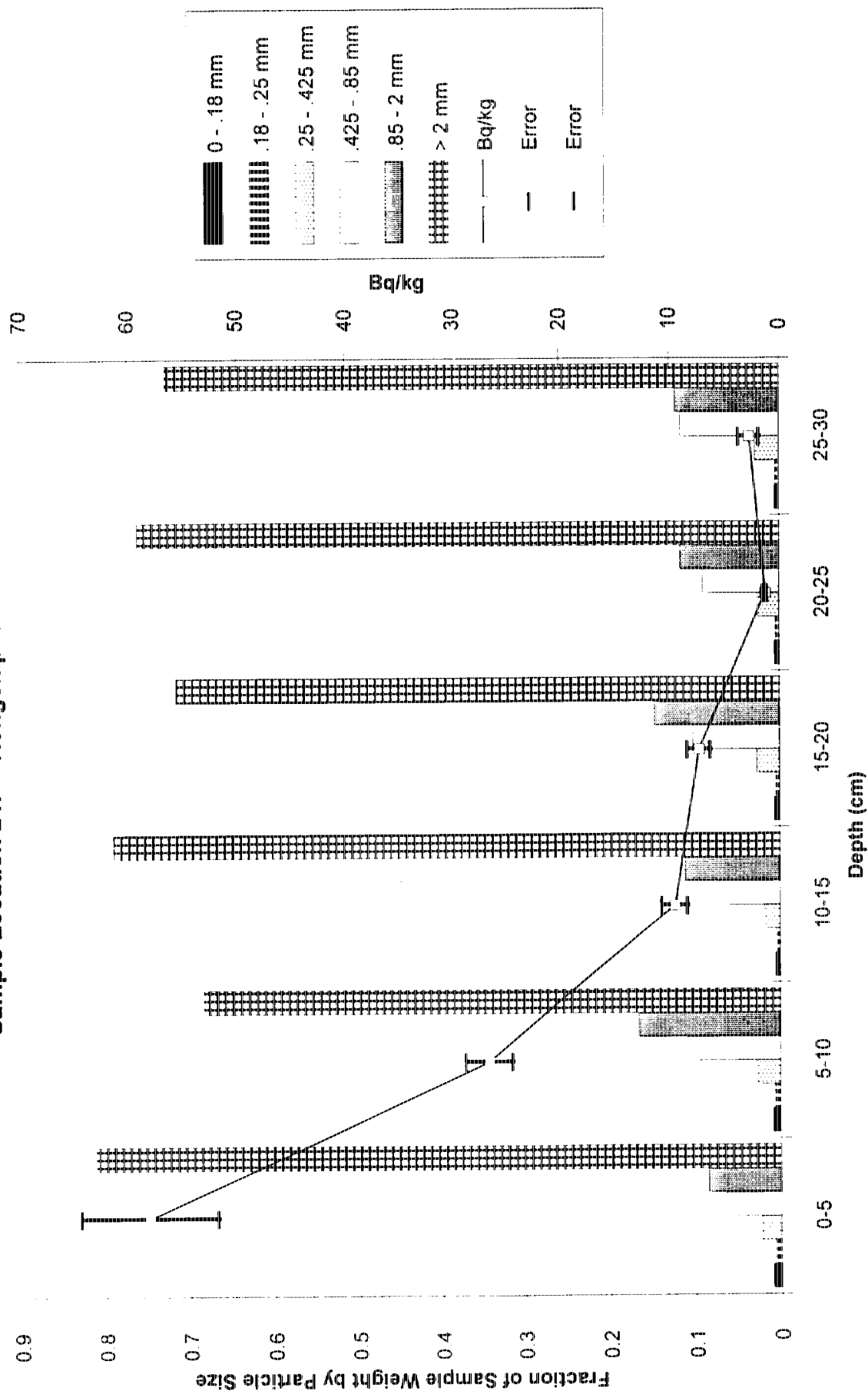


Sample Location 247 - Rongelap Island



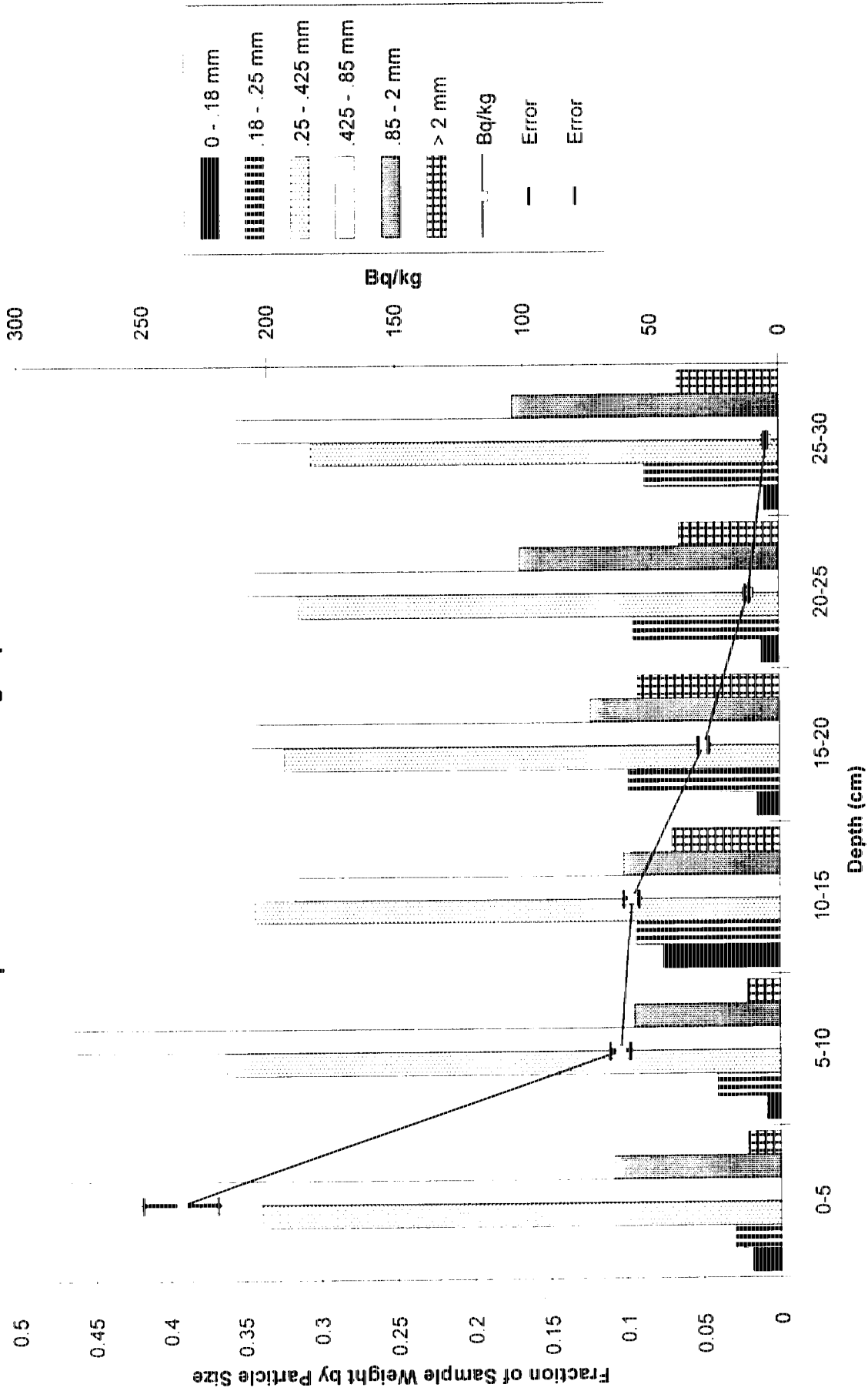
Rongelap Soil Profile 26s13 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 247 - Rongelap Island



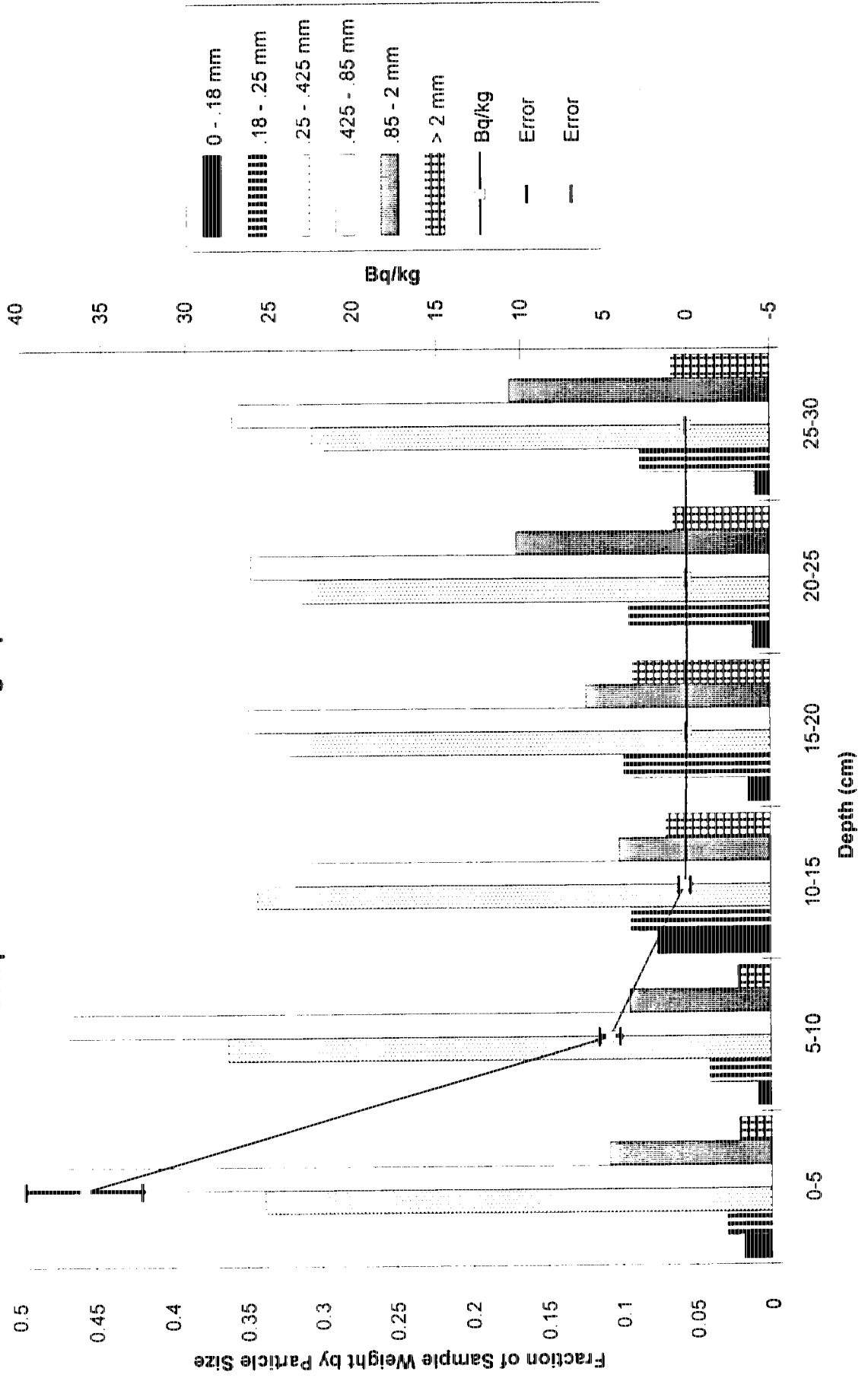
Rongelap Soil Profile 26s05 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 248 - Rongelap Island

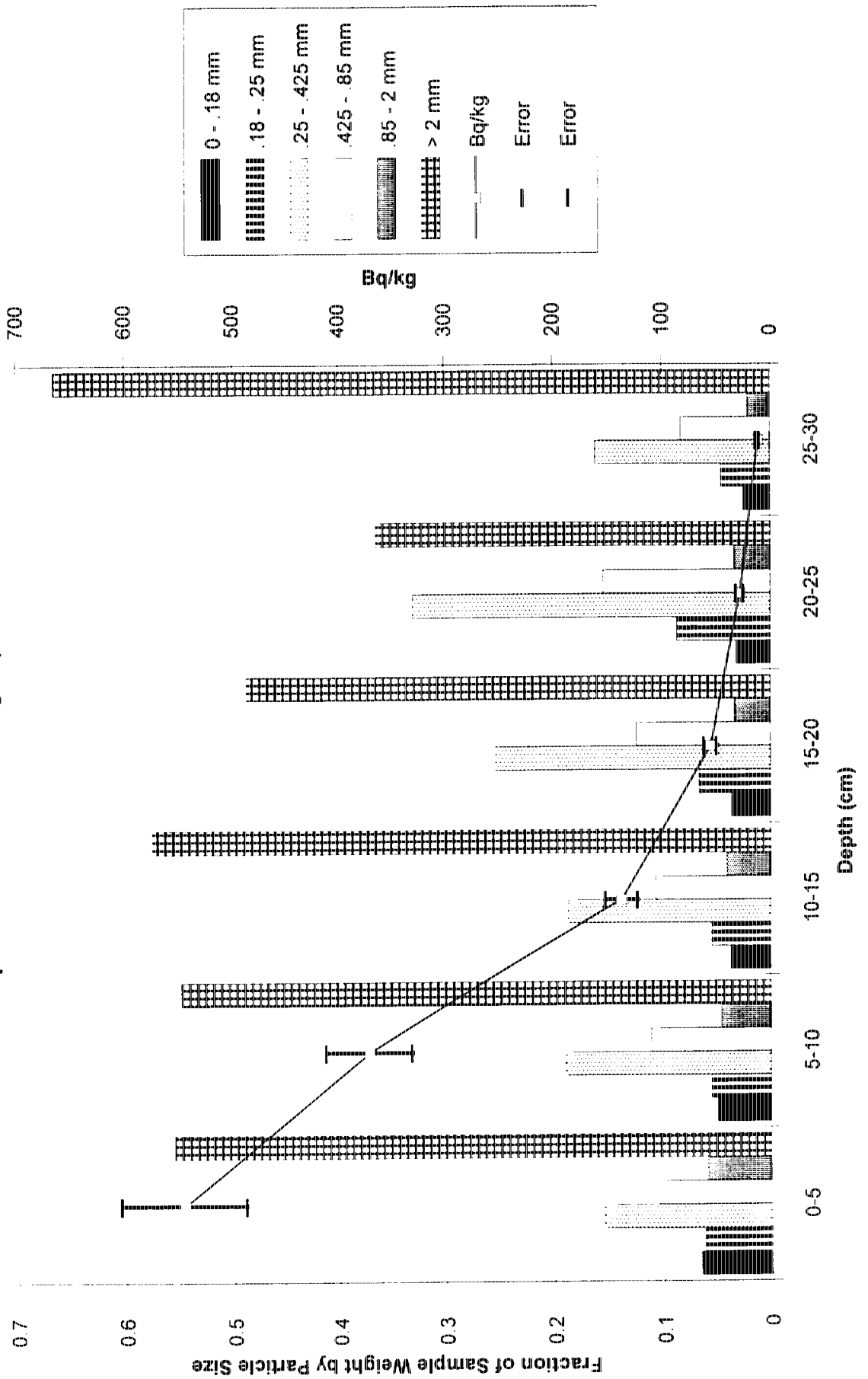


Rongelap Soil Profile 26s05 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 248 - Rongelap Island

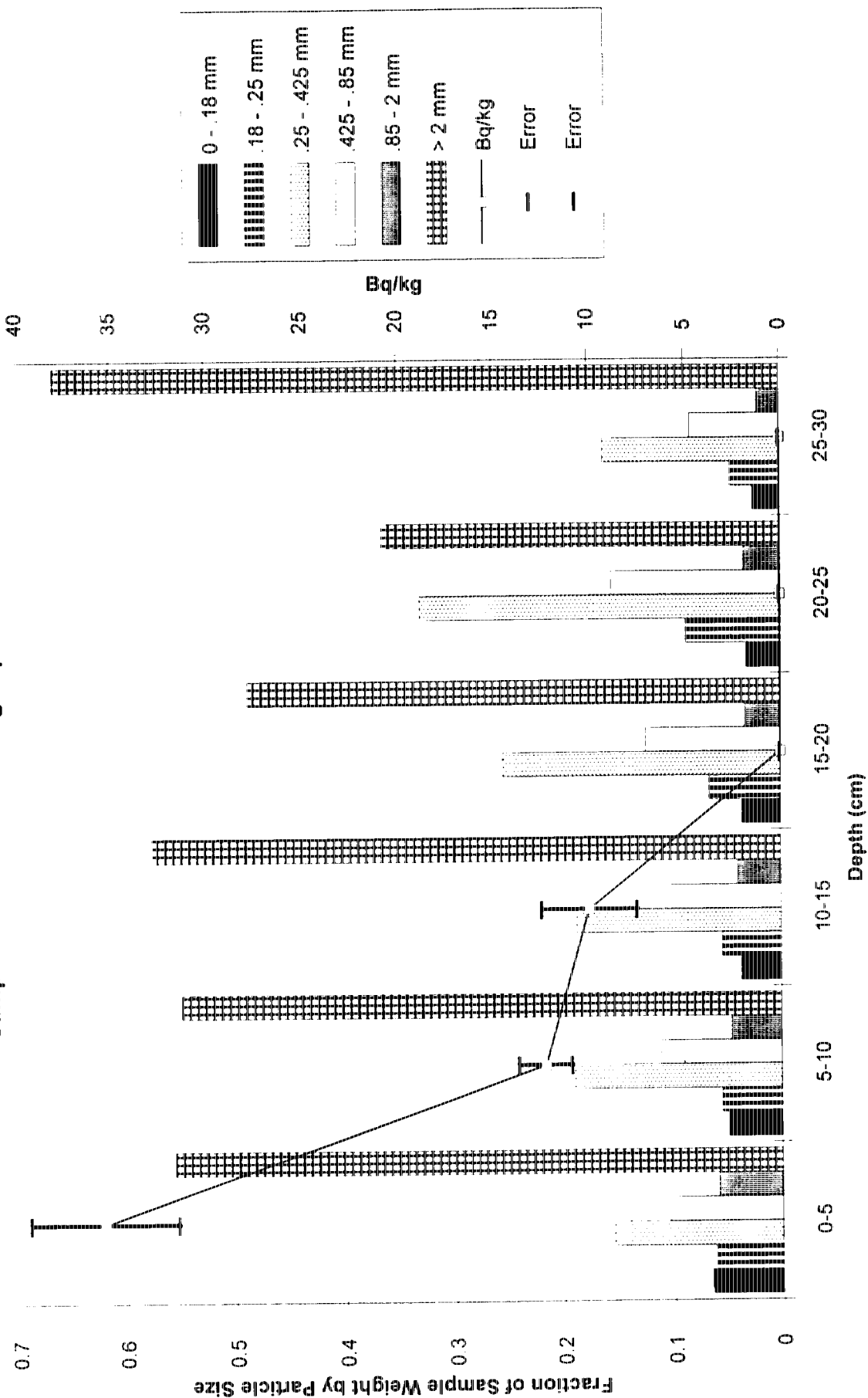


Sample Location 249 - Rongelap Island



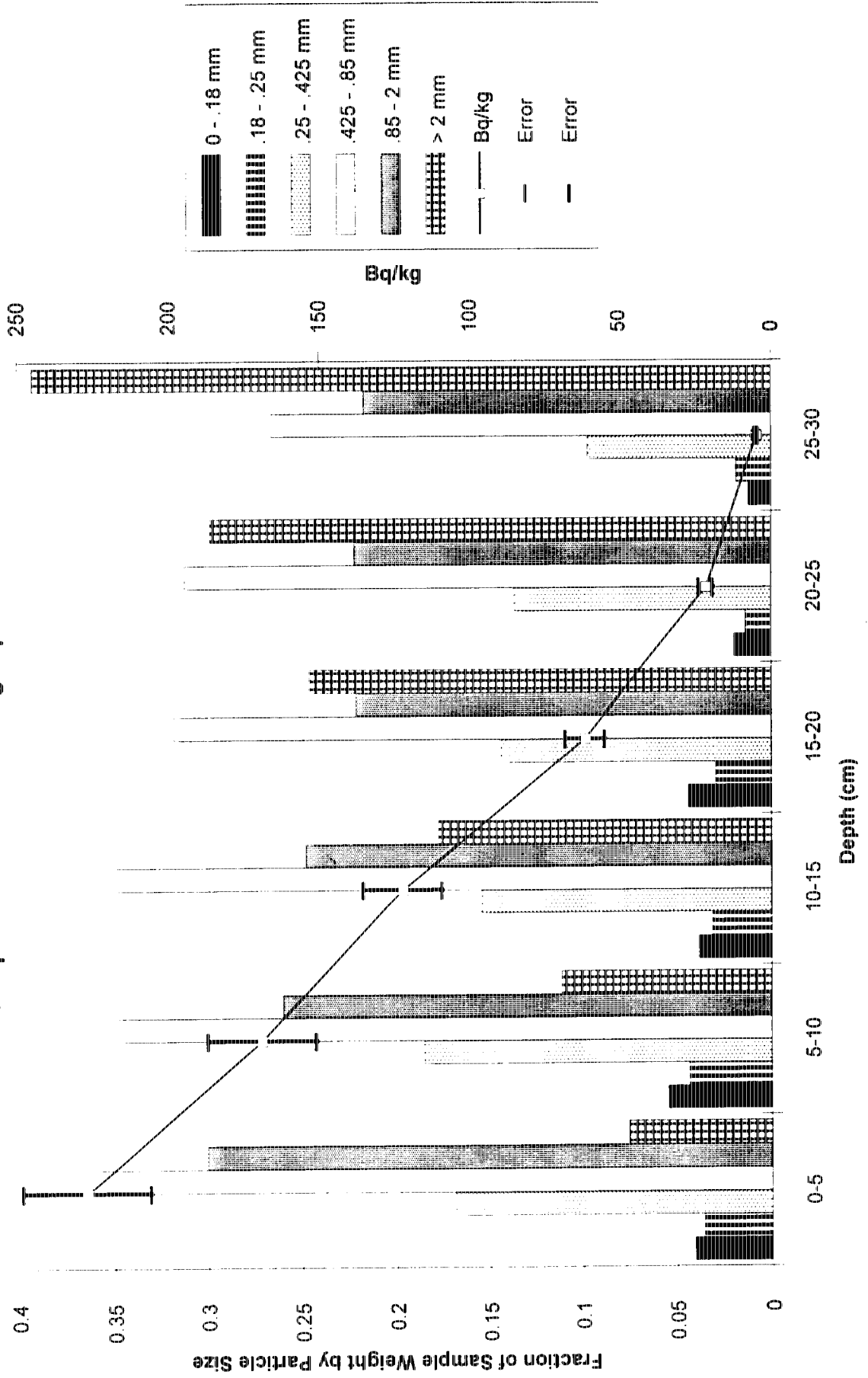
Rongelap Soil Profile 26s07 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 249 - Rongelap Island



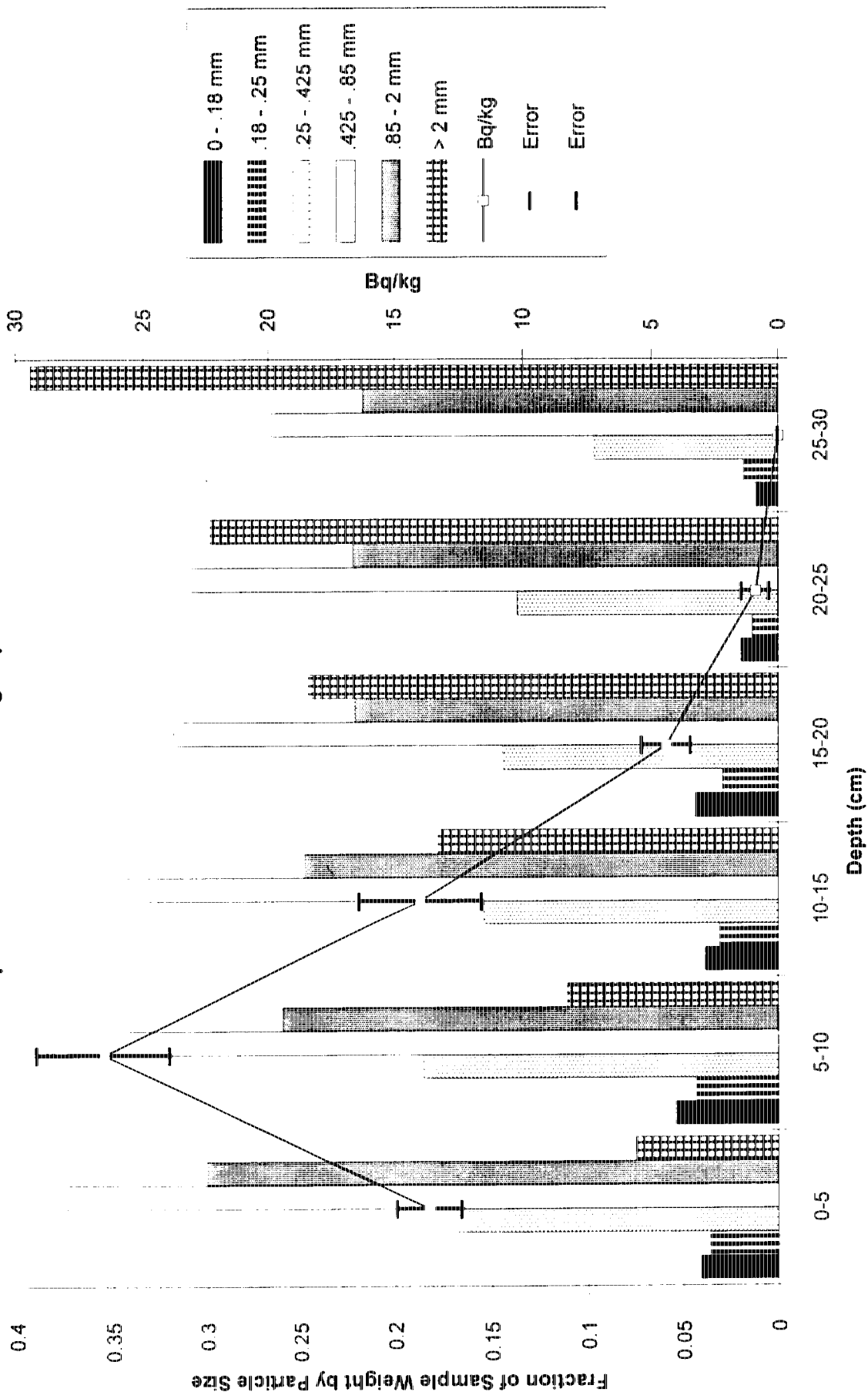
Rongelap Soil Profile 26s06 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 250 - Rongelap Island

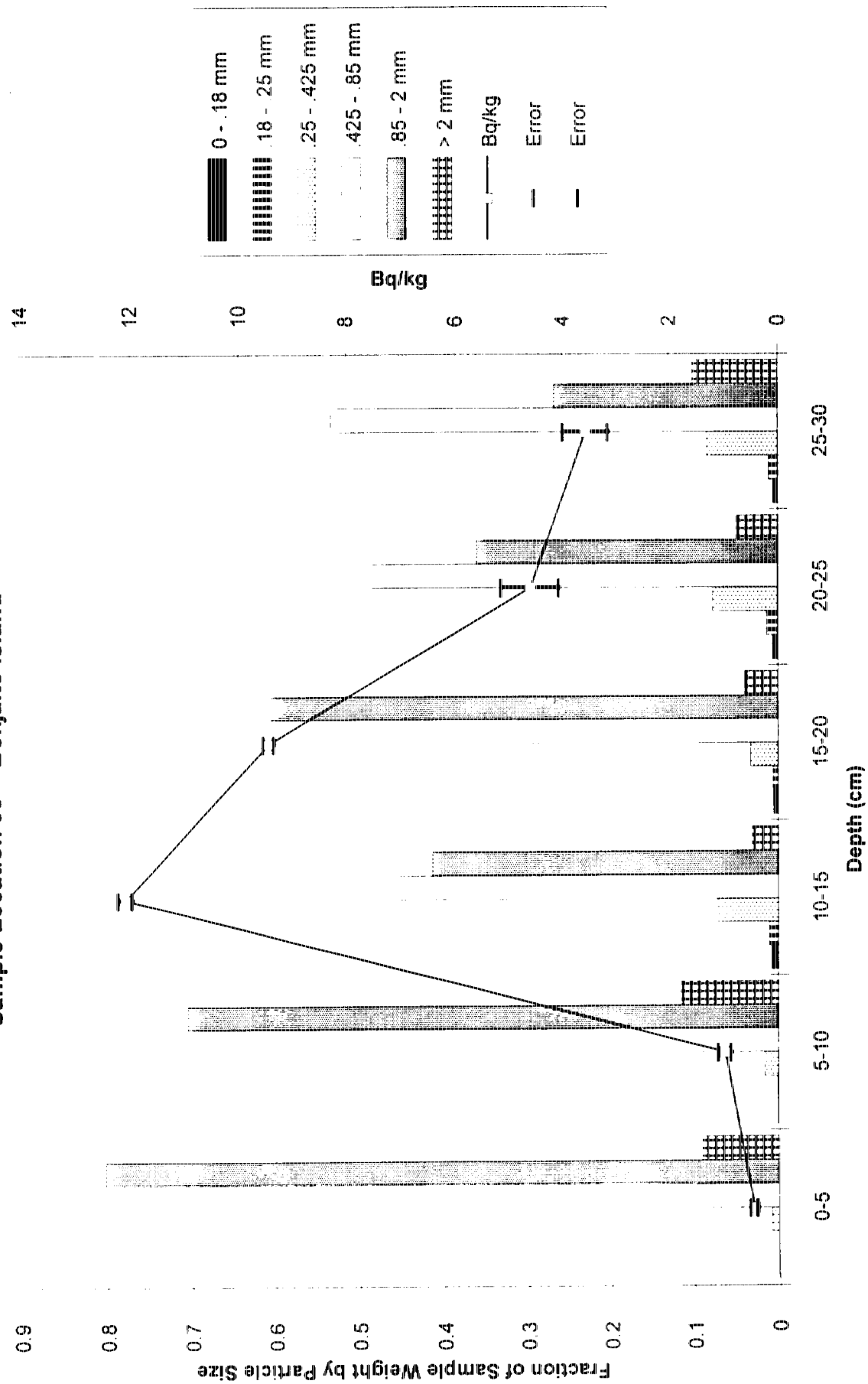


Rongelap Soil Profile 26s06 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 250 - Rongelap Island

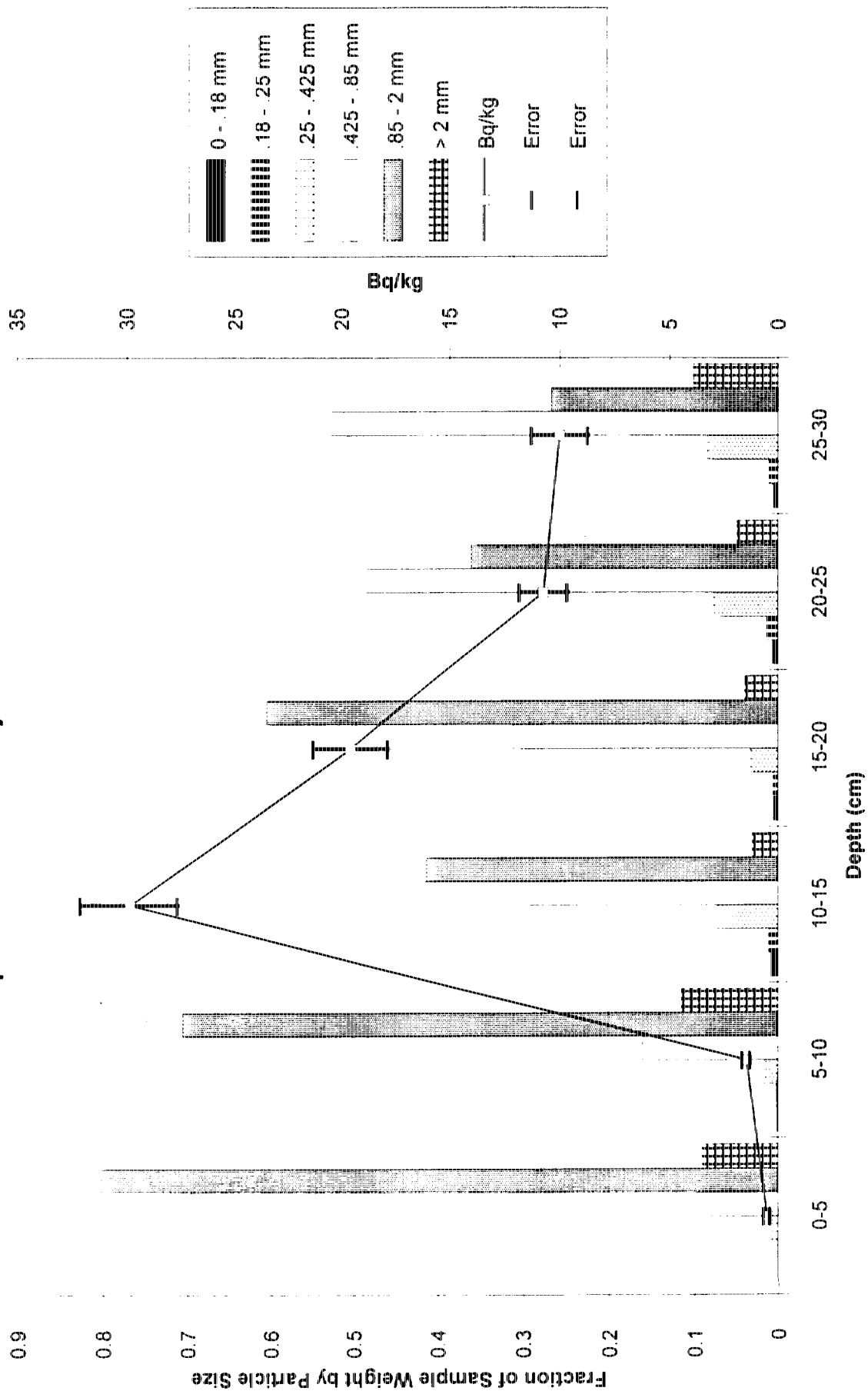


Sample Location 99 - Bokjaito Island



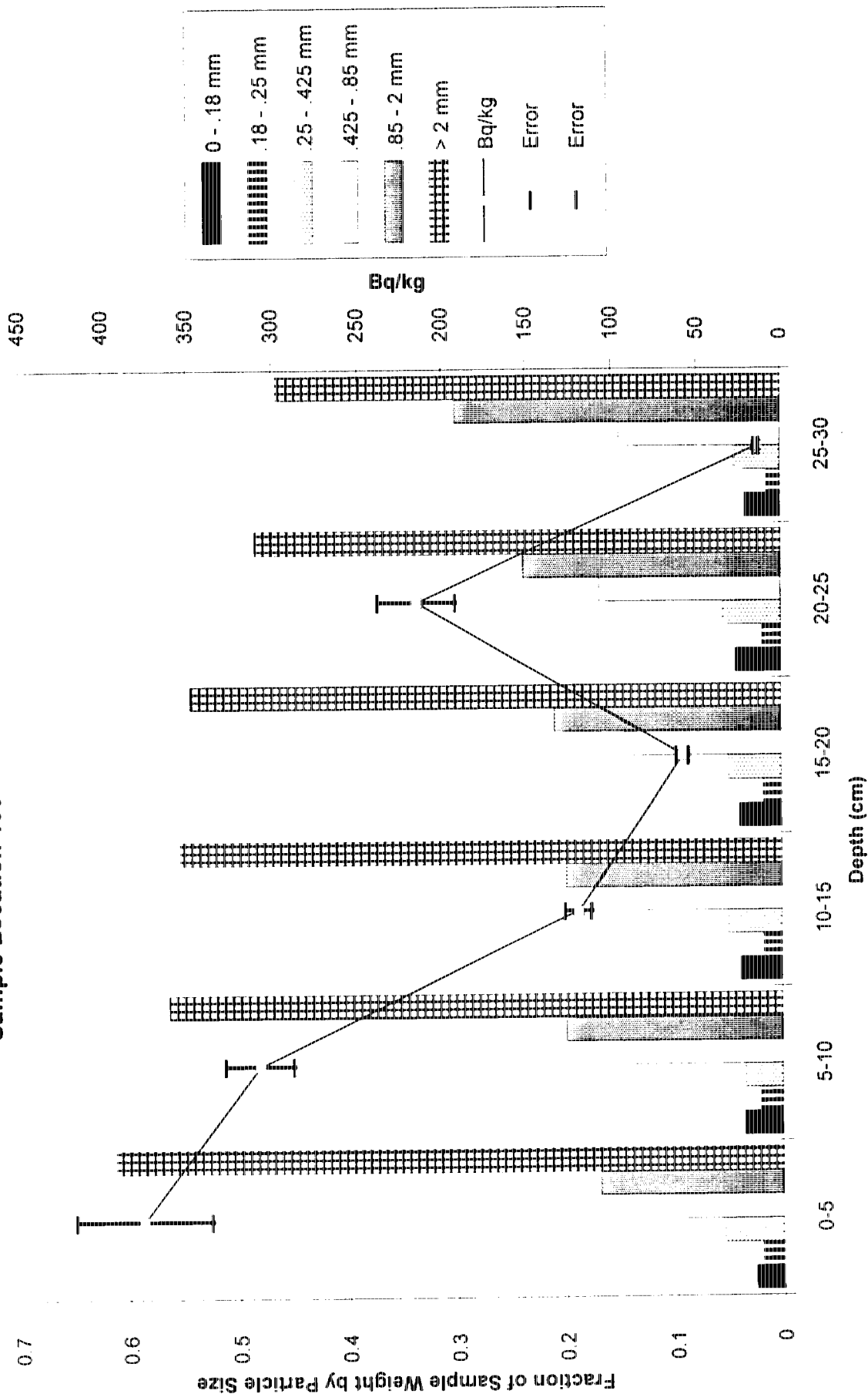
Rongelap Soil Profile 26s215 **Particle Size Distribution and Americium (Bq/kg) with Depth**

Sample Location 99 - Bokjalto Island



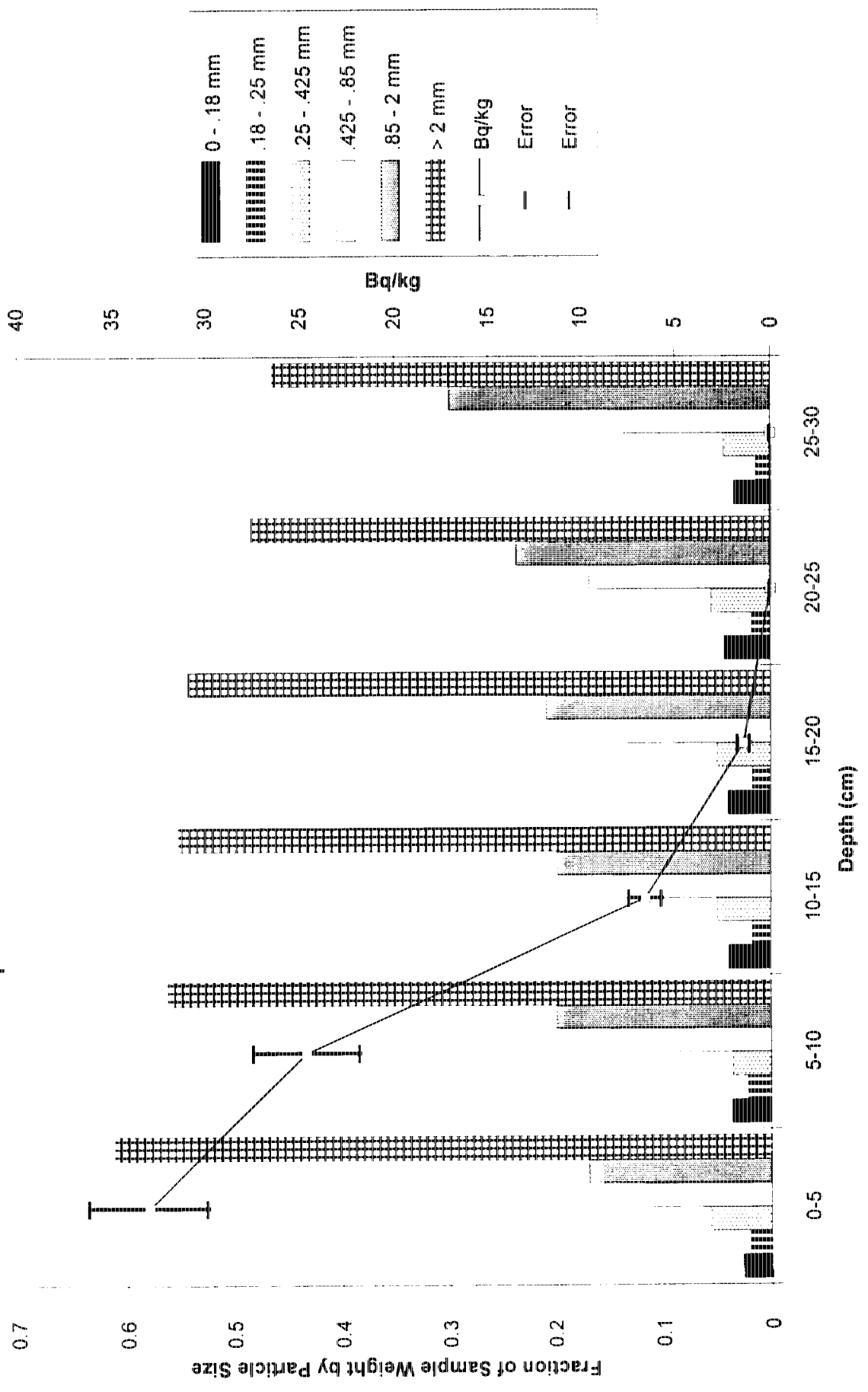
Rongelap Soil Profile 26s04 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 103 - Likoteka Island

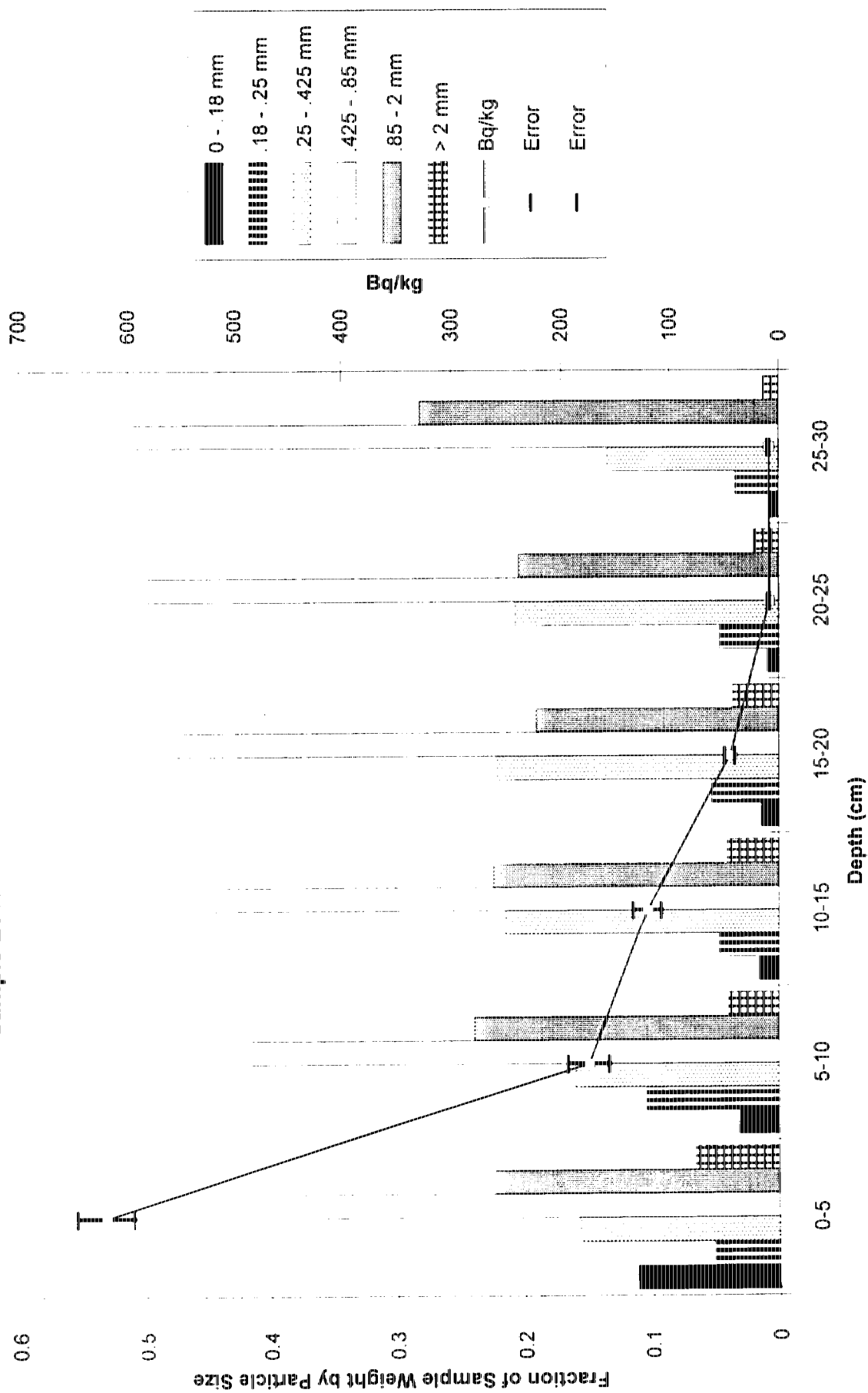


Rongelap Soil Profile 26s04 Particle Size Distribution and Americium (Bq/kg) with Depth

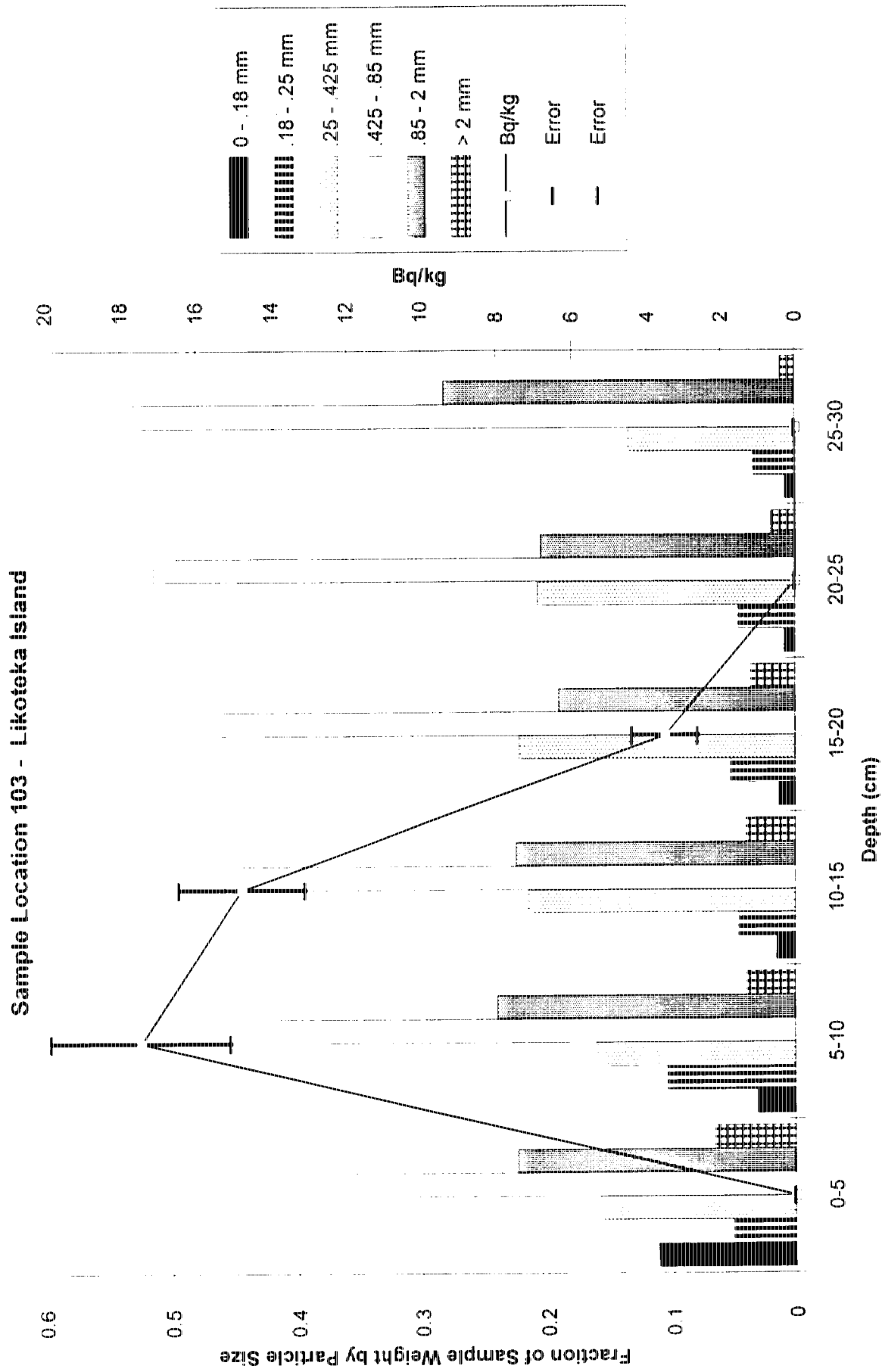
Sample Location 103 - Likoteka Island



Sample Location 103 - Likoteka Island

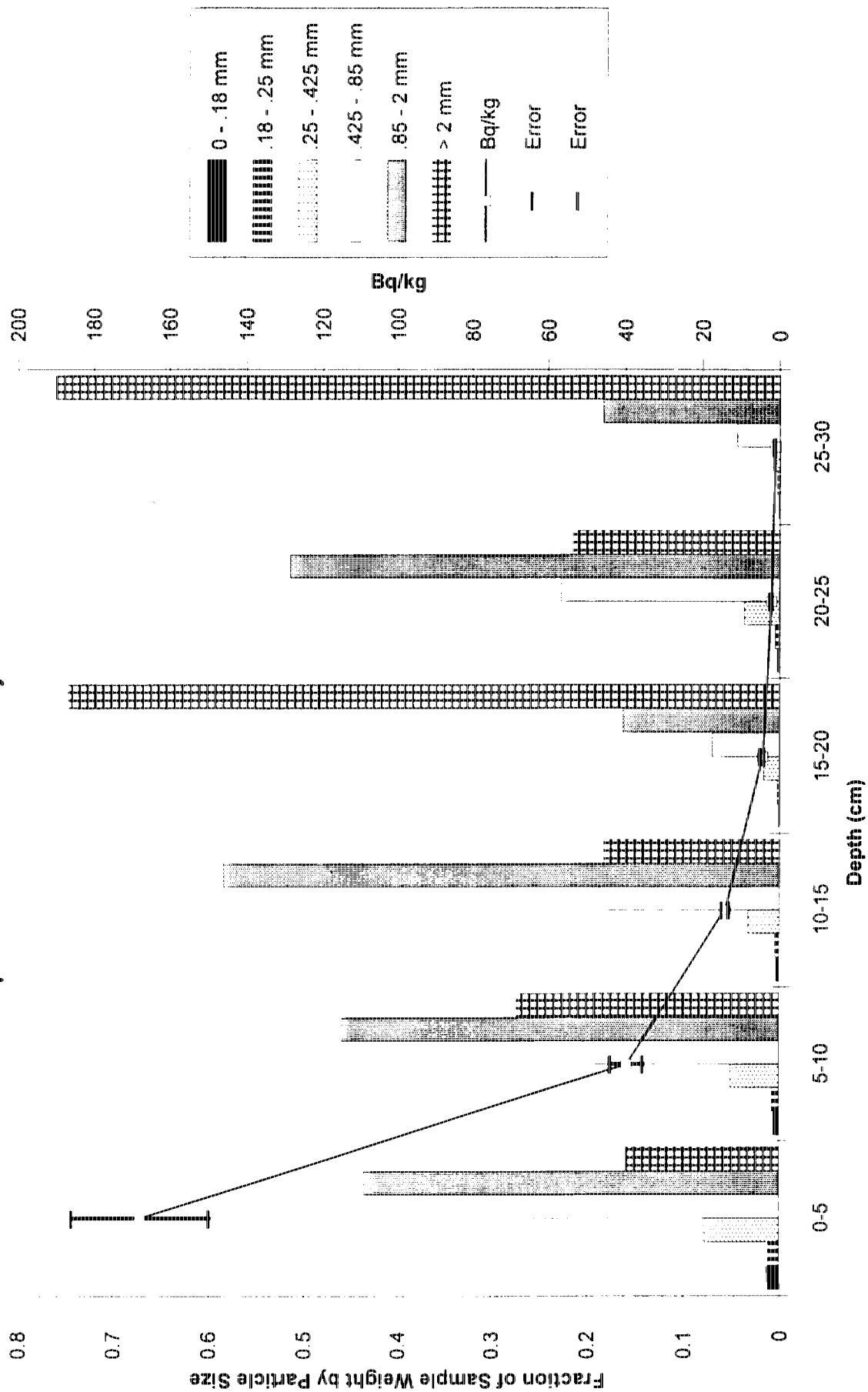


Rongelap Soil Profile 26s224 Particle Size Distribution and Americium (Bq/kg) with Depth



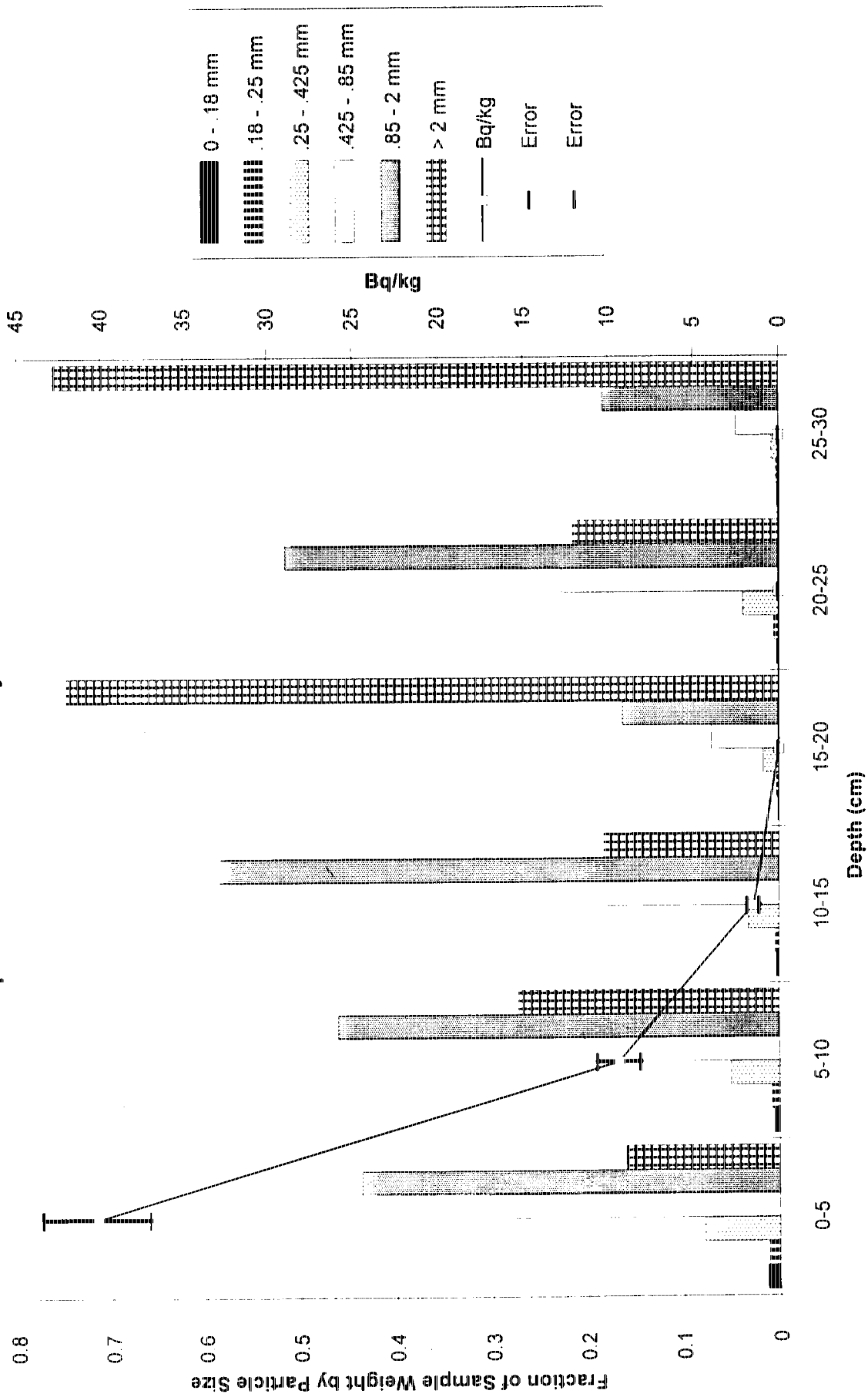
Rongelap Soil Profile 26s229 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 107 - Eonbeje Island

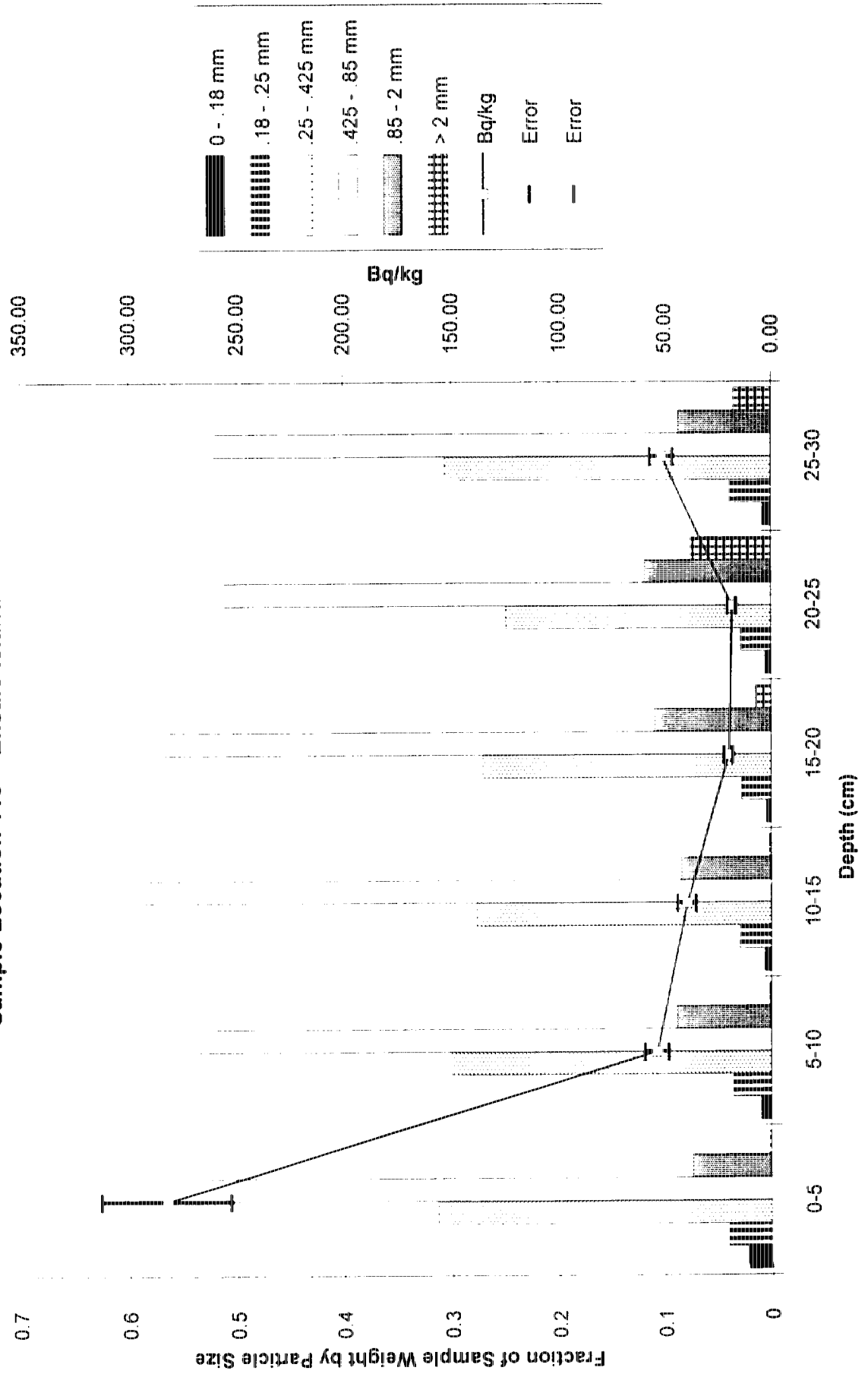


Rongelap Soil Profile 26s229 Particle Size Distribution and Americium (Bq/kg) with Depth

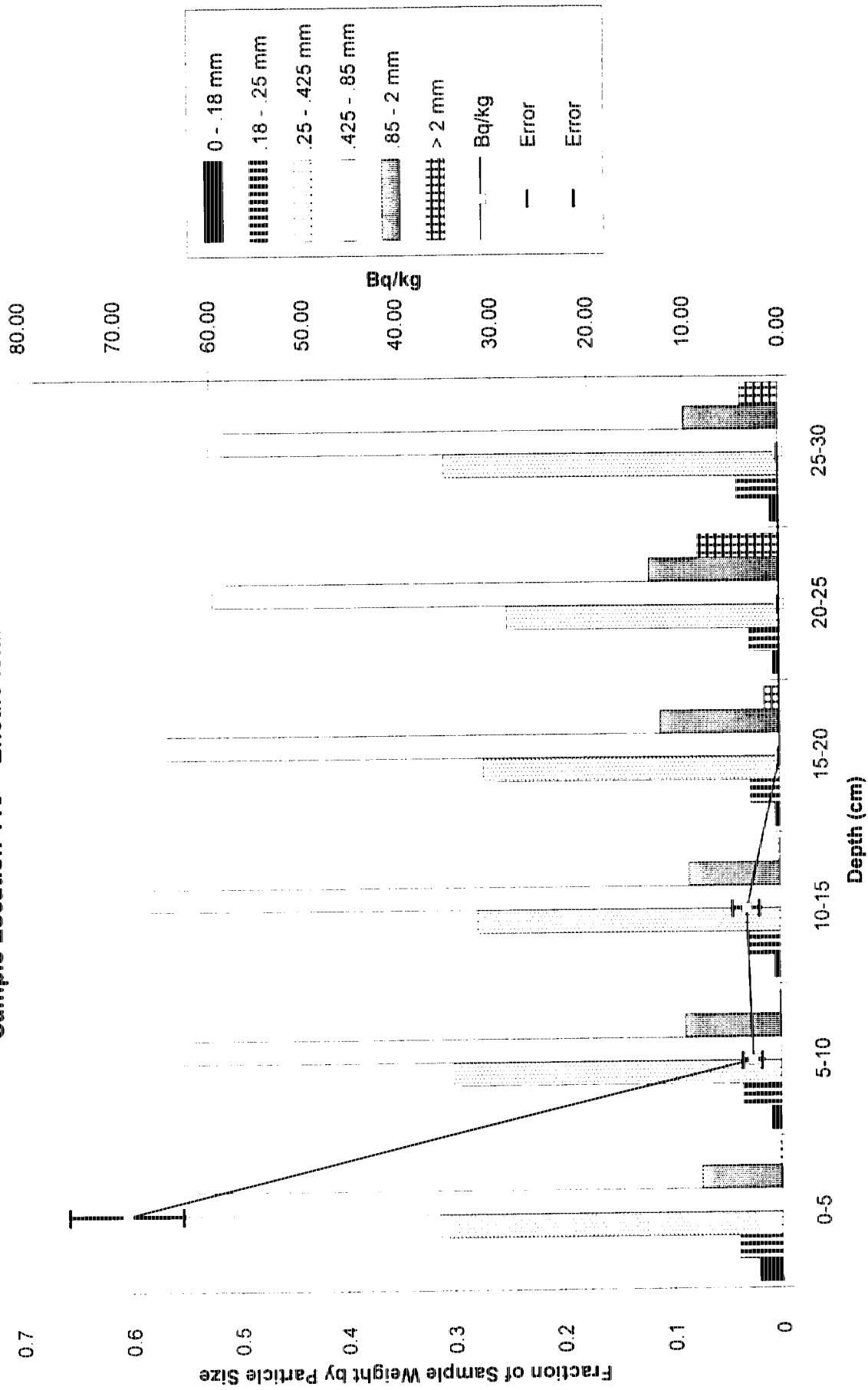
Sample Location 107 - Eonbeje Island



Sample Location 110 - Enealo Island

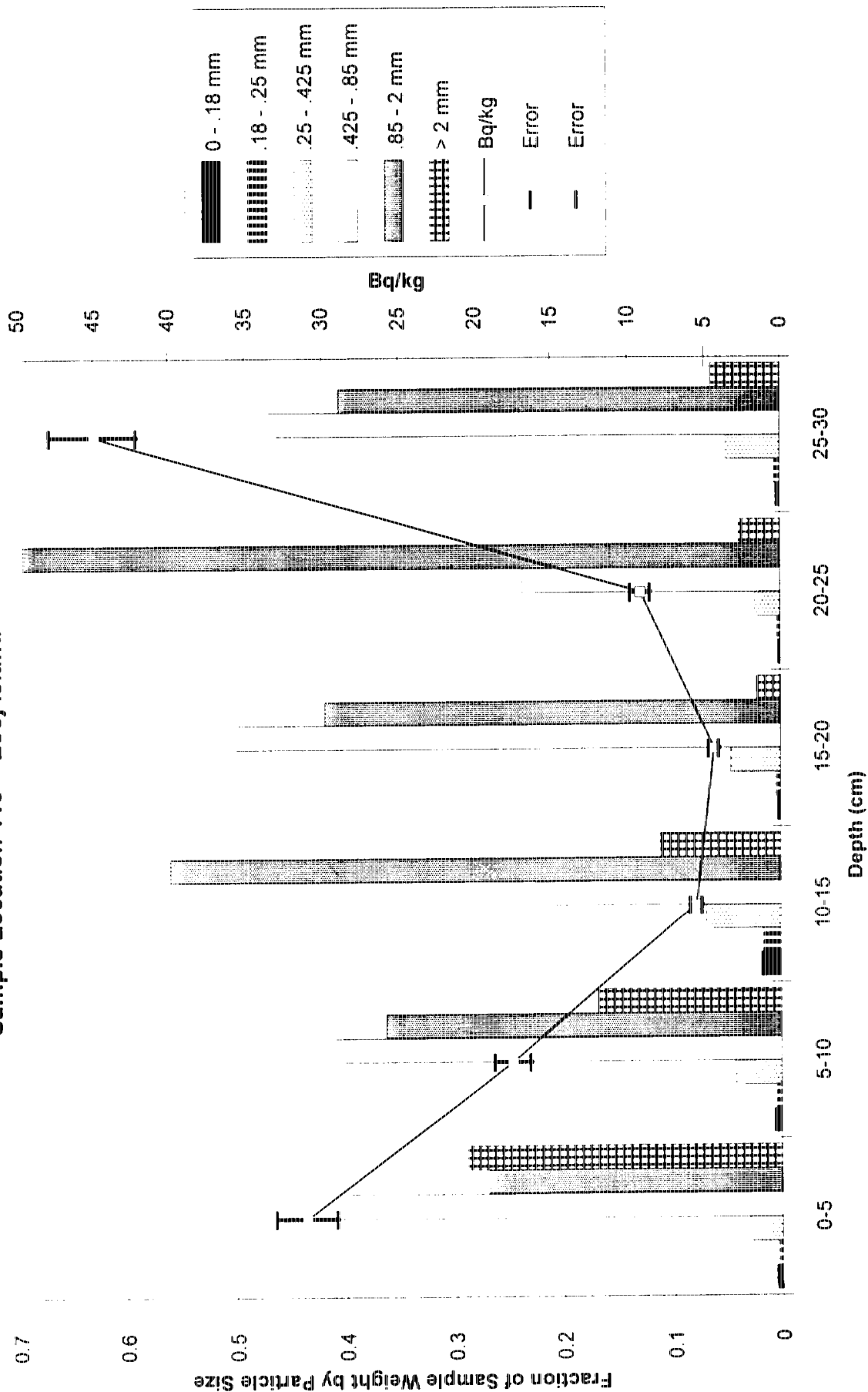


Sample Location 110 - Enealo Island



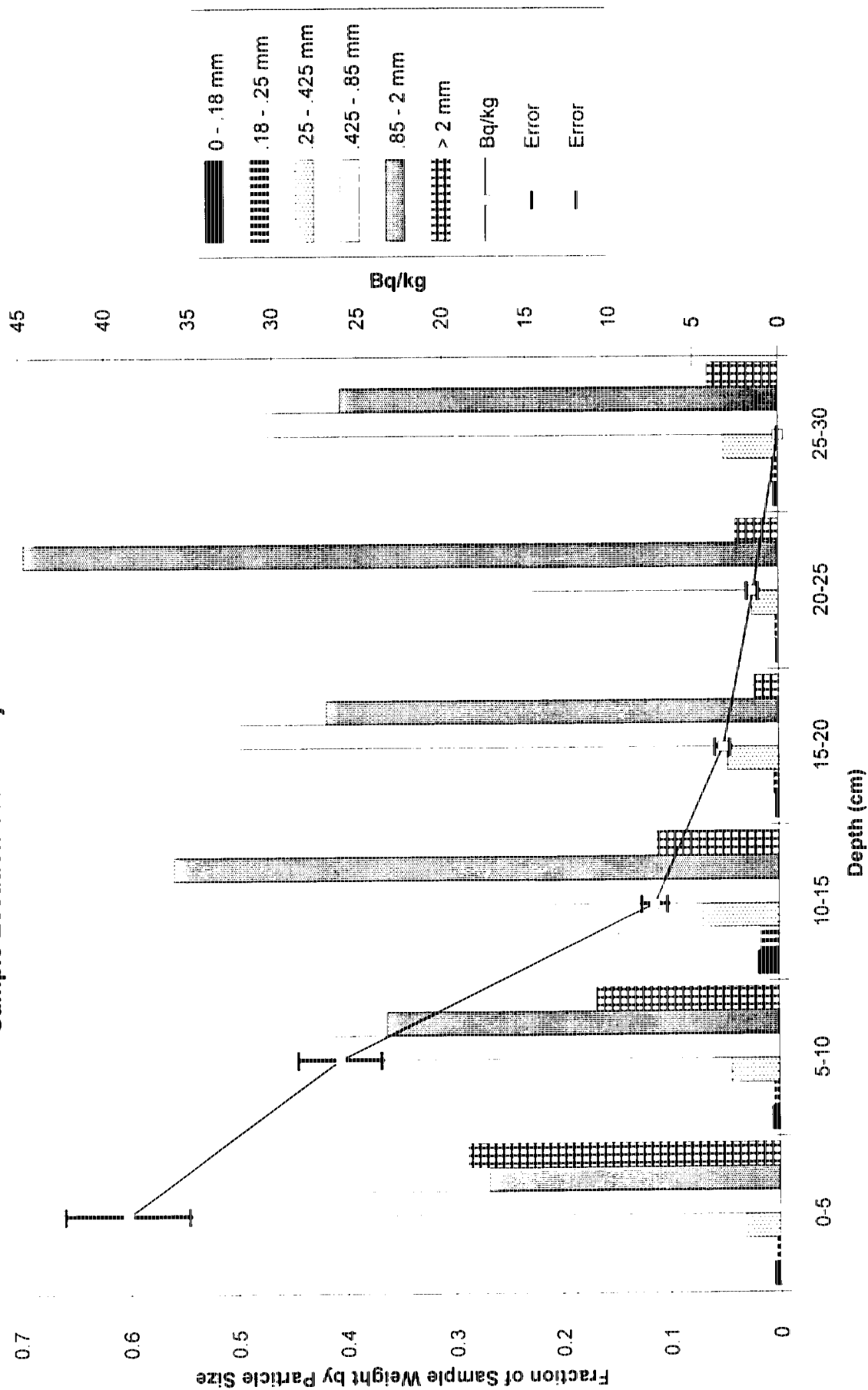
Rongelap Soil Profile 26s11 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 113 - Looj Island

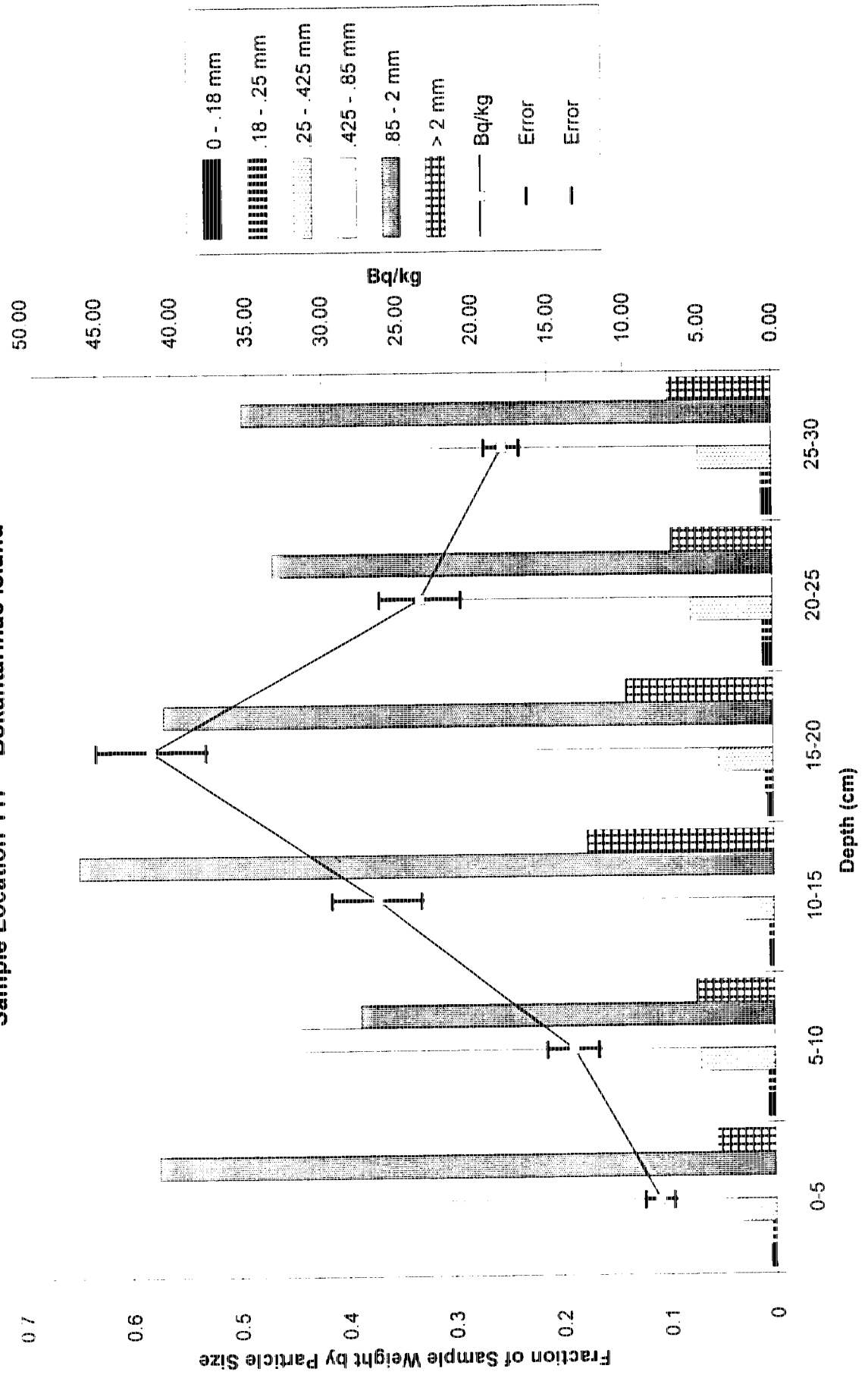


Rongelap Soil Profile 26s11 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 113 - Looj Island

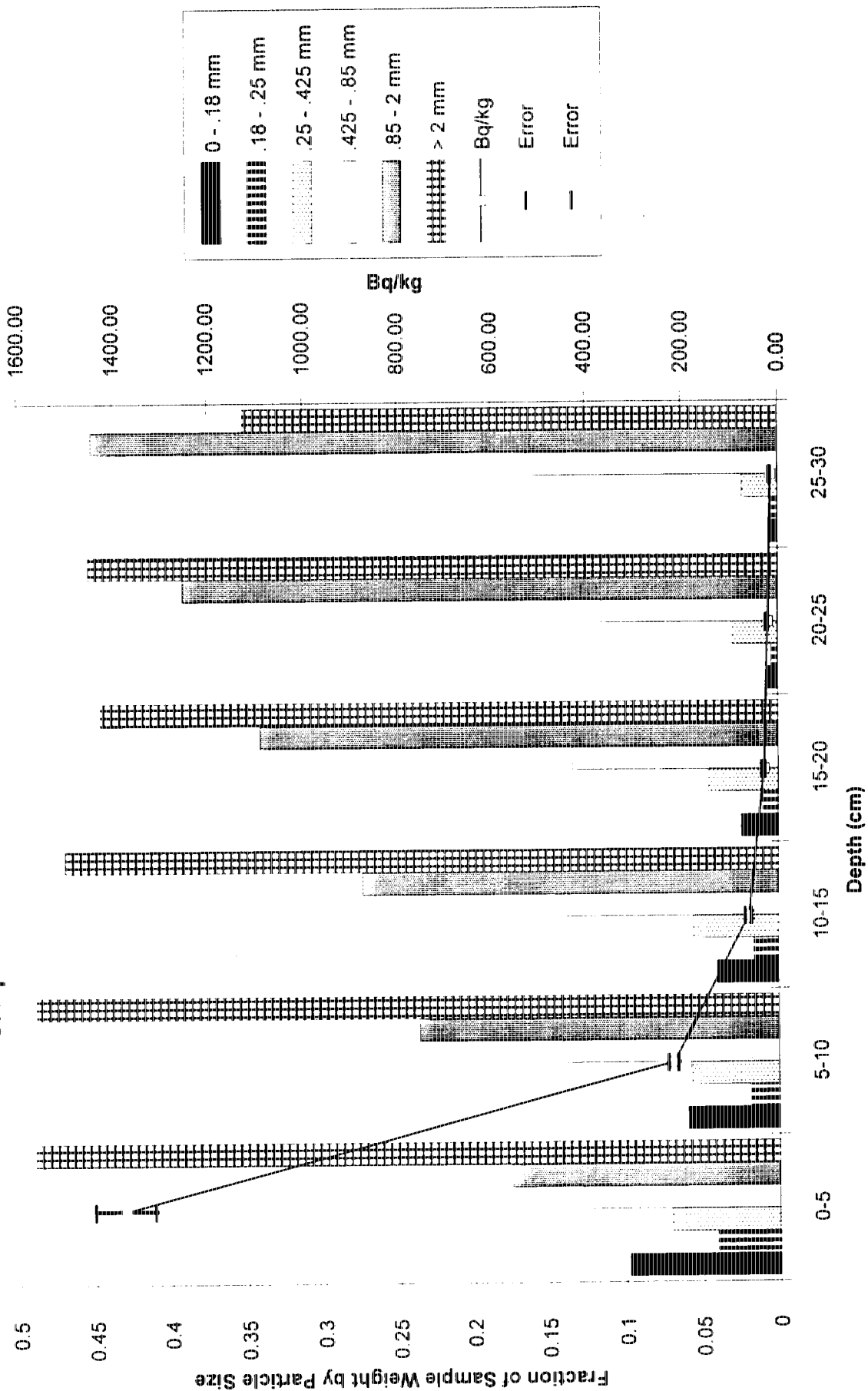


Sample Location 117 - Bokantarinæ Island



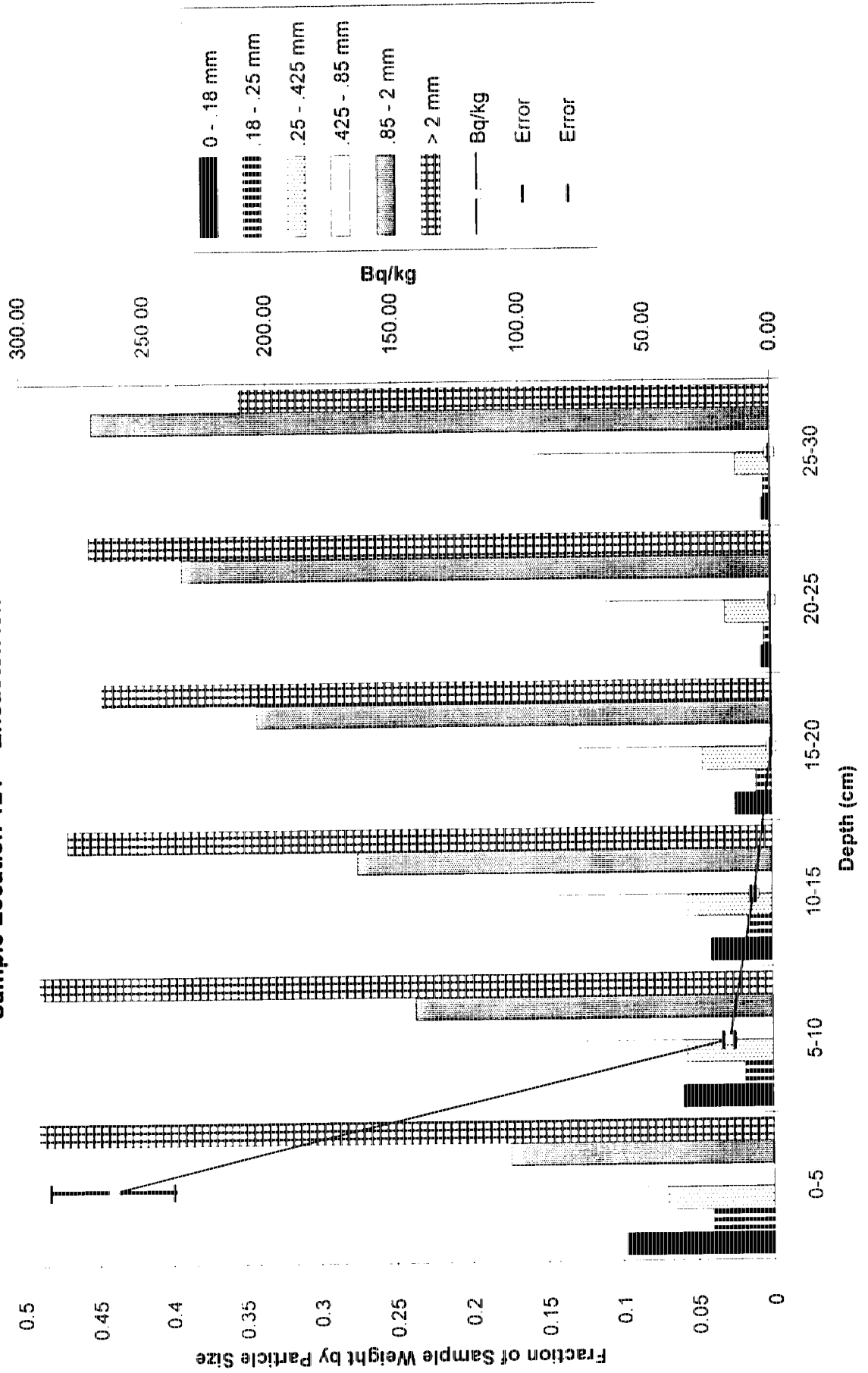
Rongelap Soil Profile 26s253 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 121 - Eneaeatok Island



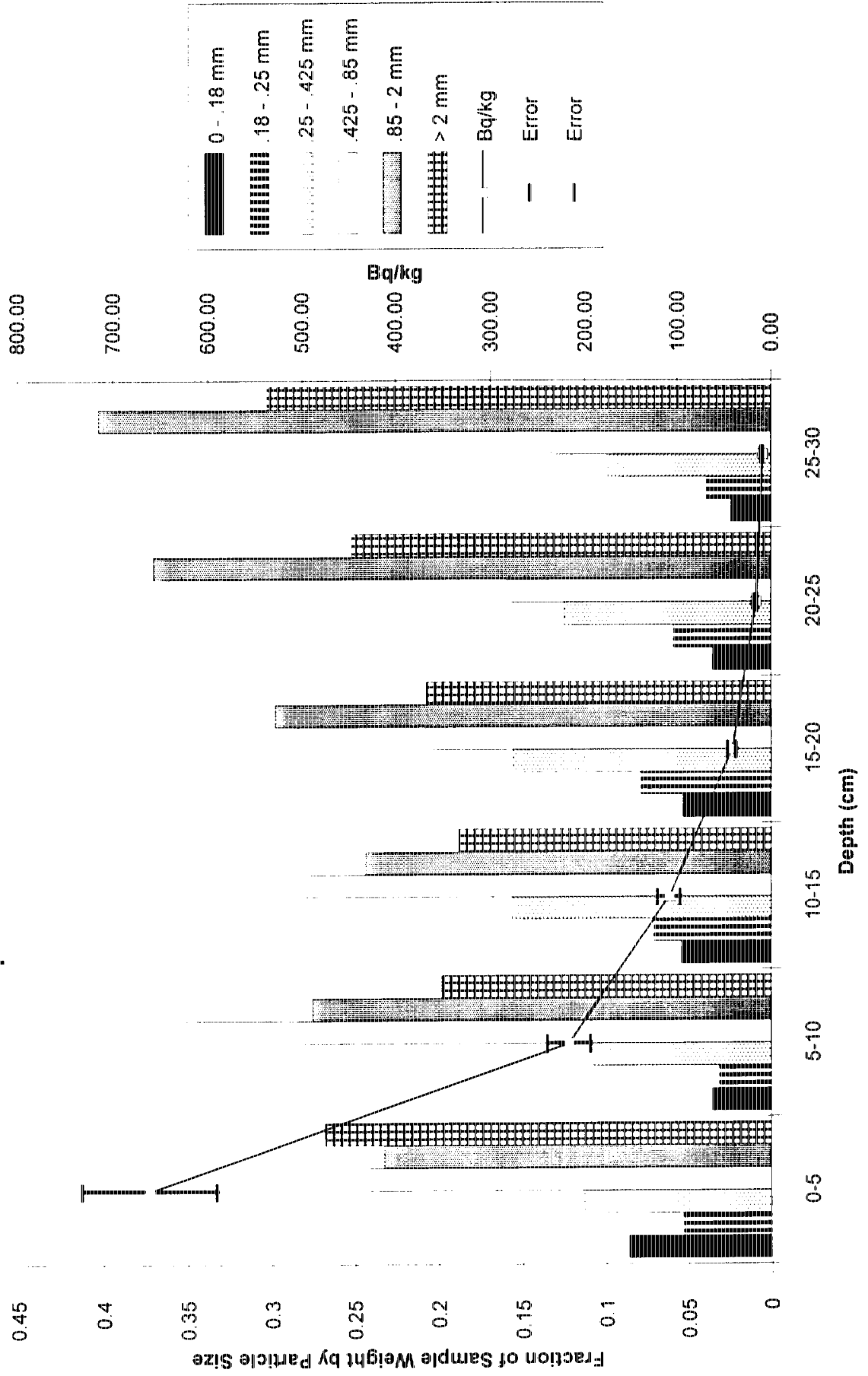
Rongelap Soil Profile 26s253 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 121 - Eneaeatok Island



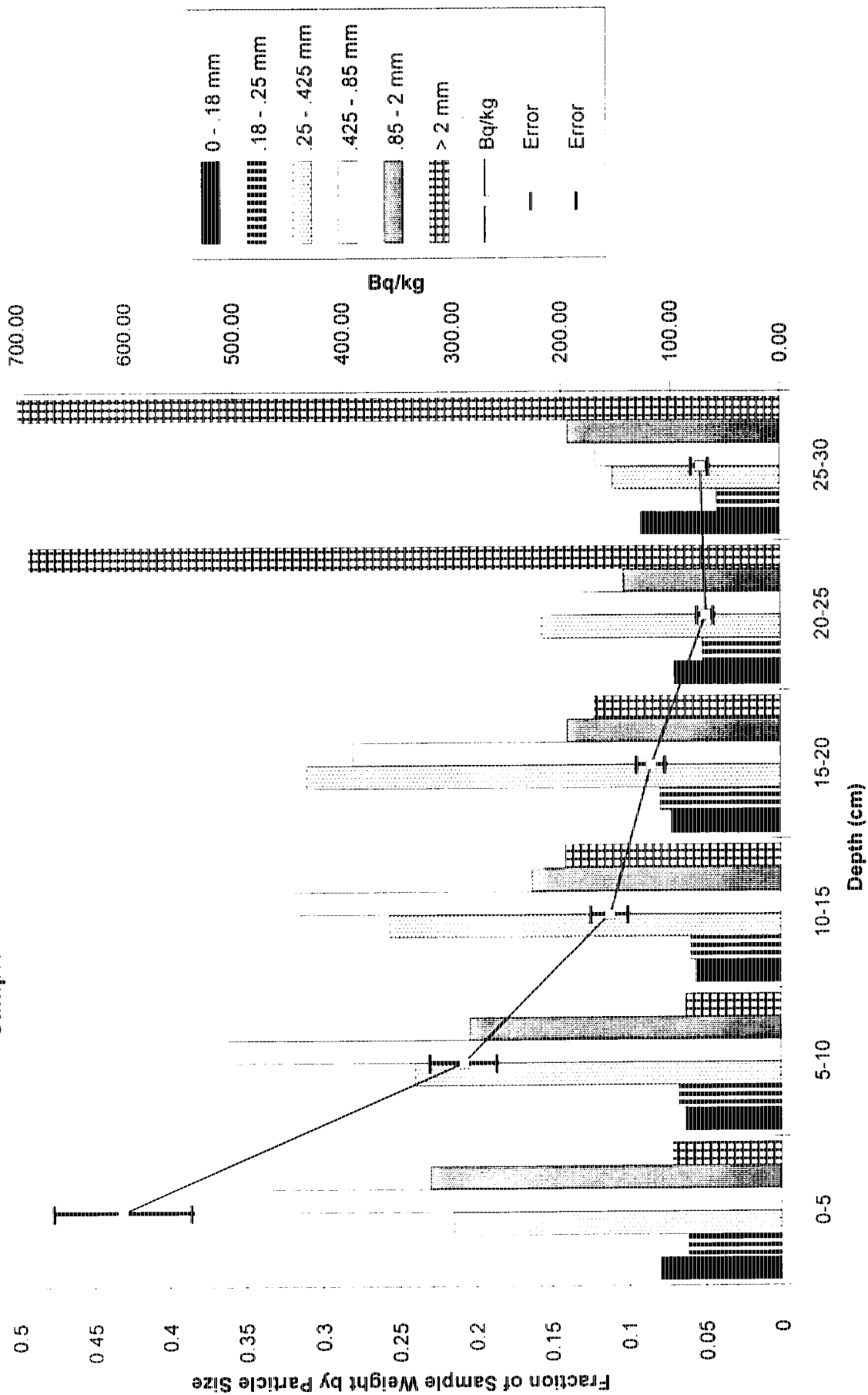
Rongelap Soil Profile 26s266 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 131 - Eneaeatok Island



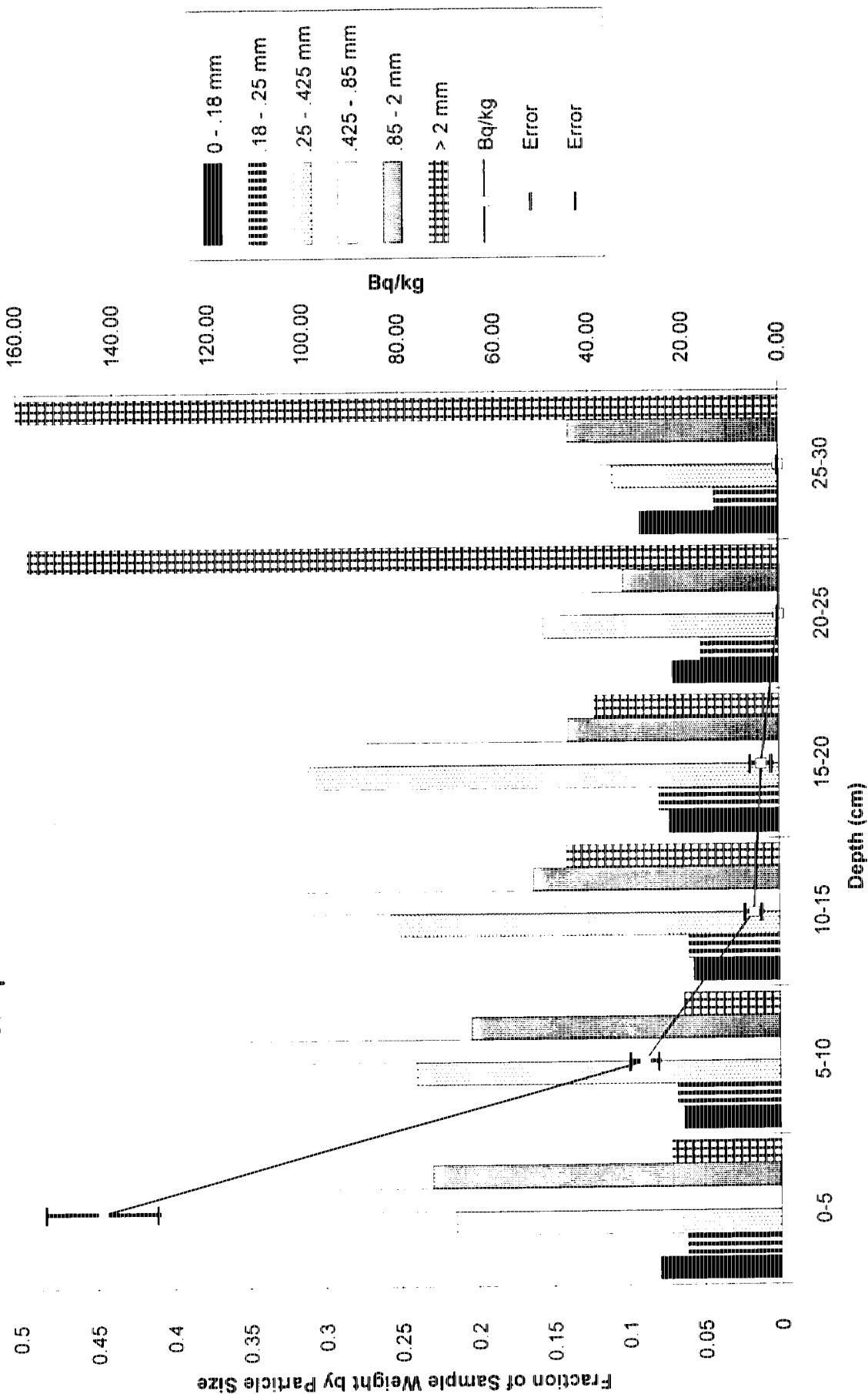
Rongelap Soil Profile 26s274 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 137 - Eneaetok Island



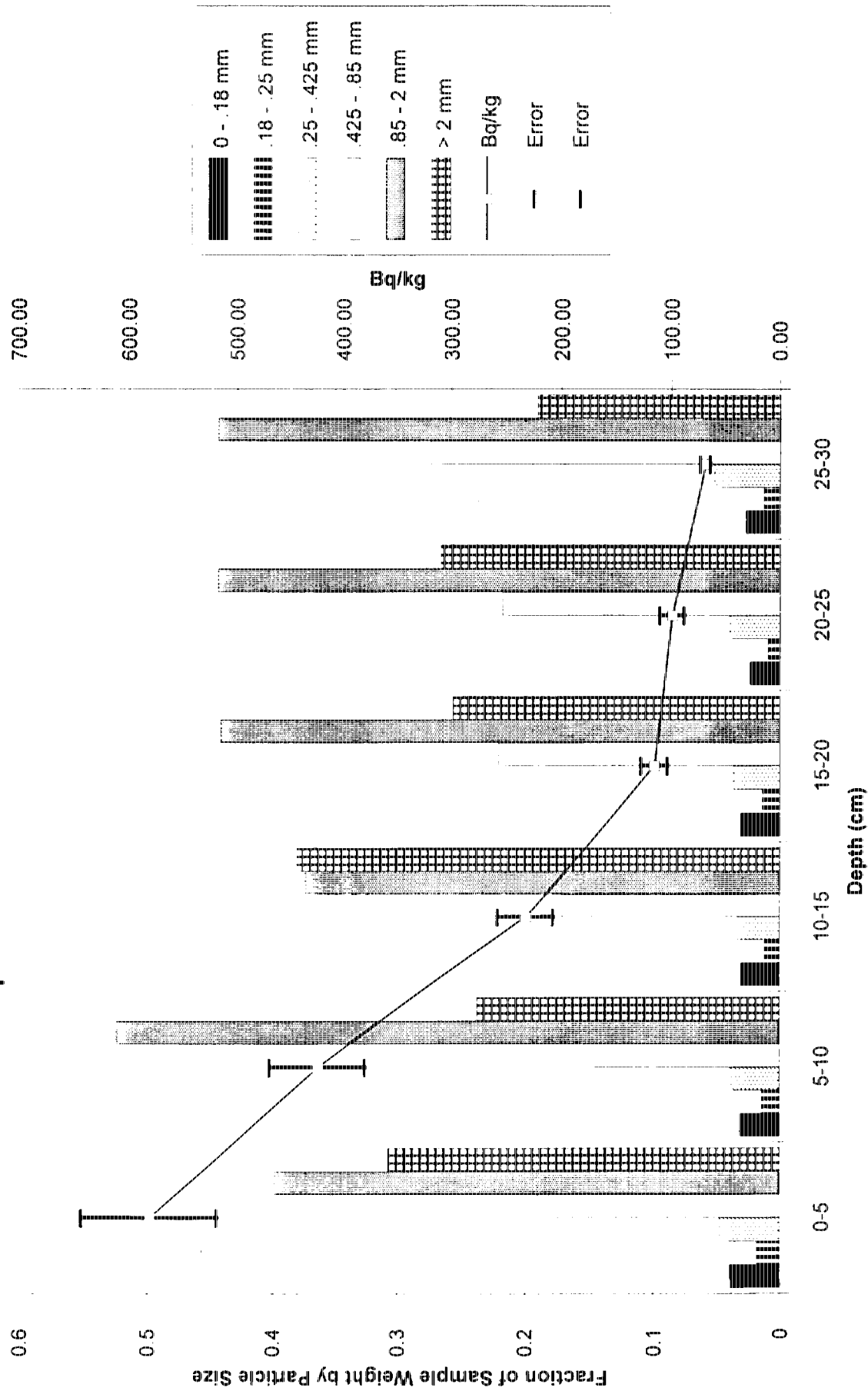
Rongelap Soil Profile 26s274 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 137 - Eneaeotok Island



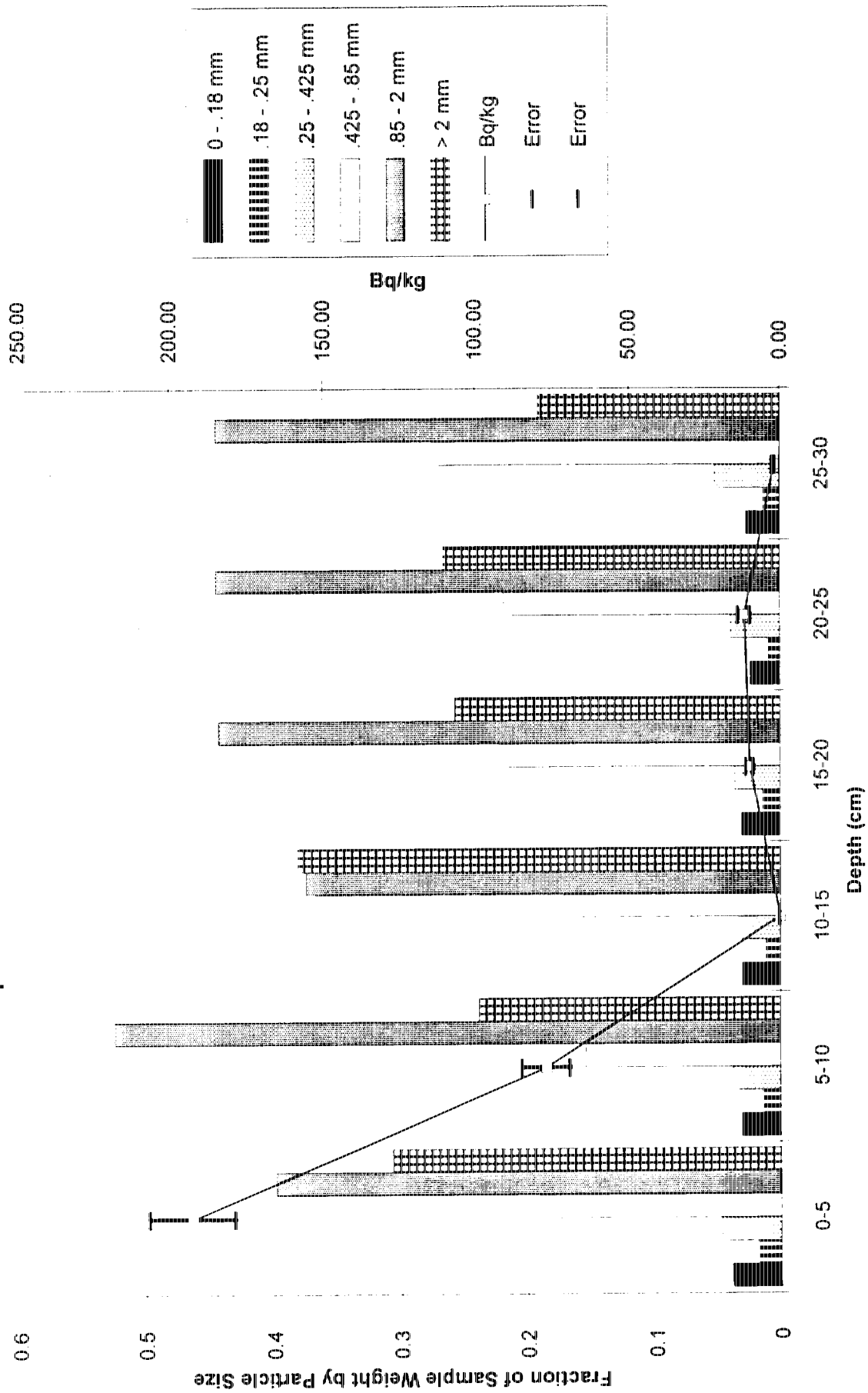
Rongelap Soil Profile 26s277 Particle Size Distribution and Cesium (Bq/kg) with Depth

Sample Location 139 - Erabot Island



Rongelap Soil Profile 26s277 Particle Size Distribution and Americium (Bq/kg) with Depth

Sample Location 139 - Erabot Island



RADIOLOGICAL DATA FROM RMI NATIONWIDE RADIOLOGICAL STUDY

Table 1. Radiological measurement data of soils from southern islands Rongelap Atoll.

Table 2. Radiological measurement data of coconuts and fruits from southern islands of Rongelap Atoll.

Table 3. Radiological measurement data of medicinal plants from southern islands of Rongelap Atoll¹.

¹Duffy, S. 1994. Cs-137 in Medicinal Plants of the Republic of the Marshall Islands. Masters Thesis. Department of Radiological Health Sciences, Colorado State University, Ft. Collins, CO.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate Meters	Y Coordinate Meters	RMI Cs-137 In-situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error +/- 1 σ	RMI Cs-137 External Dose Rate mrem/y	RMI Am-241 0.5 cm Bq/kg	RMI Am-241 0.5 cm Bq/kg Error +/- 1 σ	RMI Pu-239,240 0.5 cm Bq/kg	RMI Pu-239,240 0.5 cm Bq/kg Error +/- 1 σ	RMI Co-60 0.5 cm Bq/kg	RMI Co-60 0.5 cm Bq/kg Error +/- 1 σ
1	Rongelap	1	A1	-200	0	31000	1600	12	96	9.3	220	21	Not Detected	
1	Rongelap	2	B1	-200	-200	21000	1200	8.2	48	4.3	44	5.2	Not Detected	
1	Rongelap	3	C0	-50	-400	27000	2000	10	140	11	250	26	Not Detected	
1	Rongelap	4	C1	-200	-400	44000	2300	17	140	11	180	24	3.1	0.39
1	Rongelap	5	D0	-50	-600	24000	1800	9.3	47	4.3	130	9.3	Not Detected	
1	Rongelap	6	D1	200	-600	56000	2800	21	200	19			Not Detected	
1	Rongelap	7	E0	-70	-800	19000	1300	7.1	85	6.8	410	47	1.4	0.47
1	Rongelap	8	E1	-200	-800	38000	2300	15	95	8.8	260	26	Not Detected	
1	Rongelap	9	F1	-200	-1000	38000	2300	14.0	64	6.3	420	88	4.5	1.4
1	Rongelap	10	G1	-200	-1200	30000	1900	11						
1	Rongelap	11	H1	-200	-1400	20000	1400	7.6	73	5.4	72	12	0.74	0.31
1	Rongelap	12	H2	-320	-1480	8500	750	3.2	4.7	0.93	12	1.2	Not Detected	
1	Rongelap	13	I1	-220	-1600	12000	930	4.4	43	3.4	77	9.3	Not Detected	
1	Rongelap	14	I2	-400	-1600	43000	2600	17	51	5.1	69	13	1.1	0.59
1	Rongelap	15	I3	-530	-1600	9900	840	3.7	3.1	0.37	14	2.4	0.19	0.088
1	Rongelap	16	J1	-220	-1800	20000	1400	7.5	160	16	300	37	3.9	1.3
1	Rongelap	17	J2	-400	-1800	37000	2300	14	60	6.2	150	20	Not Detected	
1	Rongelap	18	J3	-600	-1800	29000	1800	11	61	5.8	130	17	Not Detected	
1	Rongelap	19	J4	-800	-1800	24000	1600	9.1	6.4	0.82	37	2.6	0.58	0.15
1	Rongelap	20	K1	-250	-2000	14000	1100	5.3	92	7.1	250	18	Not Detected	
1	Rongelap	21	K2	-400	-2000	30000	1900	12	110	14	170	17	Not Detected	
1	Rongelap	22	K3	-600	-2000	43000	2600	17	59	4.7	79	7.5	1.4	0.65
1	Rongelap	23	K4	-800	-2000	27000	1700	10	38	3.3	86	11	Not Detected	
1	Rongelap	24	K5	-1000	-2000	34000	2100	13	180	17	280	61	Not Detected	
1	Rongelap	25	K6	-1200	-2000	39000	2400	15	100	8.4	120	9.4	Not Detected	
1	Rongelap	26	L3	-600	-2200	14000	1000	5.2	13	1.2	34	6.8	Not Detected	
1	Rongelap	27	L4	-800	-2150	10000	840	3.8	6.6	0.90	40	3.8	Not Detected	
1	Rongelap	28	L5	-1000	-2120	26000	1700	9.9	7.0	0.79	17	2.3	Not Detected	
1	Rongelap	29	L7	-1300	-2100	23000	1600	8.9	66	6.7	150	13	Not Detected	
1	Rongelap	30	L8	-1500	-2120	51000	3000	20	160	11	230	36	2.2	0.61
1	Rongelap	31	L9	-1700	-2150	19000	1300	7.1	30	3.5	64	4.1	Not Detected	
1	Rongelap	32	L10	-1900	-2200	30000	1900	11	54	6.6	180	19	Not Detected	
1	Rongelap	33	L11	-2100	-2250	30000	1900	12	67	5.4	130	10	Not Detected	
1	Rongelap	34	M12	-2300	-2300	44000	2600	17	72	7.2	170	22	Not Detected	
1	Rongelap	35	M13	-2500	-2350	40000	2600	17	140	15	270	54	Not Detected	
1	Rongelap	36	M14	-2700	-2400	40000	2400	15	110	7.9	250	21	Not Detected	0.67
1	Rongelap	37	M15	-2900	-2450	33000	2100	13	61	6.5	120	12	Not Detected	
1	Rongelap	38	M16	-3100	-2480	35000	2200	14	34	3.7	180	22	Not Detected	

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate	Y Coordinate	RMI Cs-137 In-situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error +/- 1 σ	RMI Cs-137 External Dose Rate mrem/y	RMI Am-241 0-5 cm Bq/kg	RMI Am-241 0-5 cm Bq/kg Error +/- 1 σ	RMI Pu-239,240 0-5 cm Bq/kg	RMI Pu-239,240 0-5 cm Bq/kg Error +/- 1 σ	RMI Co-60 0-5 cm Bq/kg	RMI Co-60 0-5 cm Bq/kg Error +/- 1 σ
1	Rongelap	39	M17	-3300	-2500	40000	2400	16	43	4.2	88	8.8	0.71	0.26
1	Rongelap	40	N18	-3500	-2550	41000	2400	16	93	9.1	380	41	Not Detected	
1	Rongelap	41	N19	-3700	-2600	55000	3200	21	100	6.8	110	9.1	Not Detected	
1	Rongelap	42	O20	-3900	-2700	40000	2400	15	110	10	320	26	Not Detected	
1	Rongelap	43	O21	-4100	-2750	28000	1800	11	72	5.6	150	11	1.9	0.31
1	Rongelap	44	P22	-4300	-2900	13000	1000	5.0	36	3.7	210	25	Not Detected	
1	Rongelap	45	P23	-4500	-3020	21000	1400	8.0	31	3.4	54	4.8	Not Detected	
1	Rongelap	46	Q23	-4500	-3100	45000	2700	17	63	6.7	250	28	Not Detected	
1	Rongelap	47	P24	-4700	-3050	36000	2200	14	46	4.9	140	11	Not Detected	
1	Rongelap	48	Q25	-4900	-3100	48000	2800	18	140	10	120	16	2.3	0.72
1	Rongelap	49	Q26	-5100	-3200	16000	1200	6.2	110	8.4	180	16	Not Detected	
1	Rongelap	50	Q28	-5500	-3250	43000	2600	16	67	6.4	150	17	1.6	0.40
1	Rongelap	51	Q29	-5700	-3200	37000	2200	14	45	3.9	92	6.8	Not Detected	
1	Rongelap	52	Q30	-5900	-3200	36000	2200	14	51	4.3	71	4.8	Not Detected	
1	Rongelap	53	Q31	-6100	-3200	68000	3900	26	83	8.8	200	15	Not Detected	
1	Rongelap	54	R25	-4900	-3200	51000	3000	19	66	6.8	150	19	Not Detected	
1	Rongelap	55	R26	-5100	-3350	54000	3100	21	85	8.8	170	24	Not Detected	
1	Rongelap	56	R27	-5300	-3400	36000	2200	14	44	9.0	120	7.5	Not Detected	
1	Rongelap	57	R28	-5500	-3400	45000	2600	17	68	6.8	160	9.2	Not Detected	
1	Rongelap	58	R29	-5700	-3400	30000	1900	12	74	6.2	140	11	Not Detected	
1	Rongelap	93	R32	-6300	-3320	1000	120	0.37	0.64	0.22	5.5	1.2	Not Detected	
1	Rongelap	94	R31	-6100	-3350	29000	1600	11	15	2.2	69	15	Not Detected	
1	Rongelap	95	R30	-5900	-3400	32000	1900	12	22	3.2	110	17	Not Detected	
1	Rongelap	96	Q32	-6300	-3200	5300	460	2.0	3.9	0.96	30	6.3	Not Detected	
1	Rongelap	97	L2	-400	-2200	18000	1300	6.8	28	2.0	77	6.0	0.94	0.18
1	Rongelap	141	J3	-680	-1720	31000	1700	12	15	0.58	5.1	1.2	Not Detected	
1	Rongelap	142	J3	-640	-1720	26000	1500	9.9	11	1.4	45	3.8	Not Detected	
1	Rongelap	143	J3	-600	-1720	50000	2700	19	17	2.2	42	3.4	Not Detected	
1	Rongelap	144	J3	-560	-1720	22000	1300	8.2	18	1.9	61	4.2	Not Detected	
1	Rongelap	145	J3	-520	-1720	26000	1500	9.9	77	7.8	180	12	Not Detected	
1	Rongelap	146	J3	-520	-1760	28000	1600	11	81	10	130	28	Not Detected	
1	Rongelap	147	J3	-560	-1760	24000	1400	9.3	96	7.0	410	83	Not Detected	
1	Rongelap	148	J3	-600	-1760	27000	1600	10	88	9.6	120	36	Not Detected	
1	Rongelap	149	J3	-640	-1760	35000	2000	13	28	3.8	59	4.6	Not Detected	
1	Rongelap	150	J3	-680	-1760	55000	3000	21	33	3.7			1.2	0.57
1	Rongelap	151	J3	-680	-1800	37000	2000	14	74	6.6	140	29	Not Detected	
1	Rongelap	152	J3	-640	-1800	30000	1700	11	72	8.5	130	11	Not Detected	
1	Rongelap	153	J3	-600	-1800	29000	1700	11	23	2.9	72	9.4	Not Detected	

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate	Y Coordinate	RMI Cs-137 In-situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error	RMI Cs-137 External Dose Rate	RMI Am-241 0-5 cm Bq/kg	RMI Am-241 0-5 cm Bq/kg Error	RMI Pu-239,240 0-5 cm Bq/kg	RMI Pu-239,240 0-5 cm Bq/kg Error	RMI Co-60 0-5 cm Bq/kg	RMI Co-60 0-5 cm Bq/kg Error
				Meters	Meters	Bq/m ²	+/- 1 σ	mrem/y	Bq/kg	+/- 1 σ	Bq/kg	+/- 1 σ	Bq/kg	+/- 1 σ
1	Rongelap	154	J3	-560	-1800	29000	1700	11	58	6.7	83	15	Not Detected	
1	Rongelap	155	J3	-520	-1800	27000	1600	10	21	2.8	74	13	Not Detected	
1	Rongelap	156	J3	-520	-1840	32000	2000	12	94	8.5	420	54	Not Detected	
1	Rongelap	157	J3	-560	-1840	28000	1800	11	57	5.7	76	16	1.9	0.54
1	Rongelap	158	J3	-600	-1840	38000	2300	14	38	4.2	110	10	Not Detected	
1	Rongelap	159	J3	-640	-1840	40000	2400	15	60	4.1	130	50	1.5	0.48
1	Rongelap	160	J3	-680	-1840	48000	2800	18	42	4.8	79	6.2	Not Detected	
1	Rongelap	161	J3	-680	-1880	40000	2400	15	58	5.0	86	14	Not Detected	
1	Rongelap	162	J3	-640	-1880	35000	2200	14	14	1.6	56	6.0	0.74	0.24
1	Rongelap	163	J3	-600	-1880	22000	1500	8.4	34	3.4	44	9.5	Not Detected	
1	Rongelap	164	J3	-560	-1880	25000	1700	9.8	35	3.7	76	6.2	Not Detected	
1	Rongelap	165	J3	-520	-1880	36000	2200	14	57	6.8	120	39	Not Detected	
1	Rongelap	166	H2	-440	-1320	9600	680	3.6	17	1.6	44	3.4	0.34	0.072
1	Rongelap	167	H2	-400	-1320	33000	1900	13	45	4.6	88	6.5	Not Detected	
1	Rongelap	168	H2	-360	-1320	32000	1800	12	21	2.8	60	11	Not Detected	
1	Rongelap	169	H2	-320	-1320	27000	1600	10	84	8.7	150	9.8	Not Detected	
1	Rongelap	170	H2	-320	-1360	23000	1300	8.7	51	5.3	52	15	Not Detected	
1	Rongelap	171	H2	-360	-1360	23000	1300	8.7	61	6.2	100	15	0.79	0.44
1	Rongelap	172	H2	-400	-1360	31000	1800	12	42	5.0	65	6.0	Not Detected	
1	Rongelap	173	H2	-440	-1360	22000	1300	8.3	33	3.7	90	14	Not Detected	
1	Rongelap	174	H2	-480	-1400	30000	1700	12	15	2.0	37	4.8	Not Detected	
1	Rongelap	175	H2	-440	-1400	26000	1500	10	71	6.8	170	2.1	Not Detected	
1	Rongelap	176	H2	-400	-1400	24000	1400	9.3	78	7.5	130	11	0.72	0.39
1	Rongelap	177	H2	-360	-1400	28000	1600	11	80	7.7			1.3	0.42
1	Rongelap	178	H2	-320	-1400	22000	1300	8.4	47	5.5	76	5.3	Not Detected	
1	Rongelap	179	H2	-320	-1440	38000	2200	14	59	6.2	96	6.7	Not Detected	
1	Rongelap	180	H2	-360	-1440	19000	1200	7.2	130	7.5	220	19	Not Detected	
1	Rongelap	181	H2	-400	-1440	50000	2800	19	66	6.0	130	16	1.0	0.13
1	Rongelap	182	H2	-440	-1440	34000	2000	13	91	9.8	120	12	Not Detected	
1	Rongelap	183	H2	-480	-1440	27000	1600	10	31	2.8	74	9.8	0.50	0.089
1	Rongelap	184	H2	-480	-1480	33000	2000	13	64	6.8	120	15	Not Detected	
1	Rongelap	185	H2	-440	-1480	30000	1800	12	55	5.4	170	15	Not Detected	
1	Rongelap	186	H2	-400	-1480	40000	2300	15	290	27	460	38	5.3	0.97
1	Rongelap	187	H2	-360	-1480	32000	1900	12	45	5.2	68	6.1	Not Detected	
1	Rongelap	188	H2	-320	-1480	36000	2100	14	40	4.4	100	13	Not Detected	
1	Rongelap	189	Q29	-5700	-3200	65000	3700	25	36	4.7	86	5.8	Not Detected	
1	Rongelap	190	Q29	-5660	-3200	54000	3100	21	28	3.2	87	12	0.48	0.21
1	Rongelap	191	Q29	-5620	-3200	28000	1800	11	48	5.7	78	35	Not Detected	

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate	Y Coordinate	RMI Cs-137 In-situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error $\pm 1 \sigma$	RMI Cs-137 External Dose Rate mrem/y	RMI Am-241 0-5 cm Bq/kg	RMI Am-241 0-5 cm Bq/kg Error $\pm 1 \sigma$	RMI Pu-239,240 0-5 cm Bq/kg	RMI Pu-239,240 0-5 cm Bq/kg Error $\pm 1 \sigma$	RMI Co-60 0-5 cm Bq/kg	RMI Co-60 0-5 cm Bq/kg Error $\pm 1 \sigma$
1	Rongelap	192	Q29	-5580	-3200	31000	1900	12	36	3.7	77	7.9	Not Detected	
1	Rongelap	193	Q29	-5540	-3200	18000	1200	7.0	44	5.4	110	7.6	Not Detected	
1	Rongelap	194	Q29	-5540	-3240	64000	3600	25	57	6.5	120	16	Not Detected	
1	Rongelap	195	Q29	-5580	-3240	71000	4000	28	88	11	250	63	Not Detected	
1	Rongelap	196	Q29	-5620	-3240	54000	3000	21	120	12	340	23	Not Detected	
1	Rongelap	197	Q29	-5660	-3240	42000	2600	16	50	5.6	100	16	Not Detected	
1	Rongelap	198	Q29	-5700	-3240	47000	2800	18	46	5.5	140	17	Not Detected	
1	Rongelap	199	Q29	-5700	-3280	28000	1800	11	42	5.4	70	14	Not Detected	
1	Rongelap	200	Q29	-5660	-3280	37000	2300	14	29	3.6	64	5.4	Not Detected	
1	Rongelap	201	Q29	-5620	-3280	35000	2200	13	38	4.1	91	10	1.0	0.26
1	Rongelap	202	Q29	-5580	-3280	25000	1500	9.5	88	9.8	97	18	Not Detected	
1	Rongelap	203	Q29	-5540	-3280	42000	2500	16	77	9.3	270	46	Not Detected	
1	Rongelap	204	Q29	-5540	-3320	43000	2600	17	52	7.7	94	42	Not Detected	
1	Rongelap	205	Q29	-5580	-3320	64000	3600	25	25	6.1	53	3.5	Not Detected	
1	Rongelap	206	Q29	-5620	-3320	32000	2000	12	40	5.9	56	5.9	Not Detected	
1	Rongelap	207	Q29	-5660	-3320	35000	2100	13	43	5.5	75	9.7	Not Detected	
1	Rongelap	208	Q29	-5700	-3320	29000	1900	11	28	3.6	49	6.2	Not Detected	
1	Rongelap	209	Q29	-5700	-3360	29000	1800	11	35	4.4	91	9.3	Not Detected	
1	Rongelap	210	Q29	-5660	-3360	40000	2400	15	39	4.7	75	5.9	Not Detected	
1	Rongelap	211	Q29	-5620	-3360	19000	1300	7.4	40	4.7	53	6.4	Not Detected	
1	Rongelap	212	Q29	-5580	-3360	34000	2100	13	34	4.4	67	7.8	Not Detected	
1	Rongelap	213	Q29	-5540	-3360	28000	1800	11	37	4.8	53	6.3	Not Detected	
1	Rongelap	214	R27	-5380	-3320	56000	3200	22	110	11	120	16	Not Detected	
1	Rongelap	215	R27	-5340	-3320	53000	3100	21	71	7.5	150	12	Not Detected	
1	Rongelap	216	R27	-5300	-3320	51000	3000	20	96	10	85	7.0	Not Detected	
1	Rongelap	217	R27	-5260	-3320	37000	2300	14	60	6.3	120	15	Not Detected	
1	Rongelap	218	R27	-5220	-3320	26000	1700	9.8	43	5.0	79	8.0	Not Detected	
1	Rongelap	219	R27	-5220	-3360	53000	3000	20	110	12	120	12	Not Detected	
1	Rongelap	220	R27	-5260	-3360	47000	2700	18	44	5.6	75	4.7	Not Detected	
1	Rongelap	221	R27	-5300	-3360	47000	2800	18	110	11	210	22	1.9	0.66
1	Rongelap	222	R27	-5340	-3360	35000	2100	13	20	2.4	34	3.7	Not Detected	
1	Rongelap	223	R27	-5380	-3360	48000	2800	18	69	7.8	140	20	1.6	0.55
1	Rongelap	224	R27	-5380	-3400	46000	2700	18	50	5.7	110	7.6	Not Detected	
1	Rongelap	225	R27	-5340	-3400	58000	3400	22	64	7.3	120	8.2	Not Detected	
1	Rongelap	226	R27	-5300	-3400	51000	3000	20	110	12	110	15	Not Detected	
1	Rongelap	227	R27	-5260	-3400	39000	2400	15	76	9.5	140	9.5	Not Detected	
1	Rongelap	228	R27	-5220	-3400	34000	2100	13	94	9.9	120	9.2	Not Detected	
1	Rongelap	229	R27	-5220	-3440	47000	2800	18	86	9.7	190	13	Not Detected	

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate Meters	Y Coordinate Meters	RMI Cs-137 In-situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error +/- 1 σ	RMI Cs-137 External Dose Rate mrem/y	RMI Am-241 0-5 cm Bq/kg	RMI Am-241 0-5 cm Bq/kg Error +/- 1 σ	RMI Pu-239,240 0-5 cm Bq/kg	RMI Pu-239,240 0-5 cm Bq/kg Error +/- 1 σ	RMI Co-60 0-5 cm Bq/kg	RMI Co-60 0-5 cm Bq/kg Error +/- 1 σ
1	Rongelap	230	R27	-5260	-3440	63000	3600	24	91	9.4	140	13	2.8	0.41
1	Rongelap	231	R27	-5300	-3440	50000	3100	19	48	5.6	85	10	Not Detected	
1	Rongelap	232	R27	-5340	-3440	39000	2400	15	67	7.6	160	8.4	Not Detected	
1	Rongelap	233	R27	-5380	-3440	56000	3200	21	150	14	280	22	3.0	0.85
1	Rongelap	234	R27	-5380	-3480	39000	2300	15	27	3.7	53	7.6	Not Detected	
1	Rongelap	235	R27	-5340	-3480	42000	2700	16	100	10			Not Detected	
1	Rongelap	236	R27	-5300	-3480	40000	2400	15	100	11	190	13	Not Detected	
1	Rongelap	237	R27	-5260	-3480	40000	2400	15	74	8.0	150	10	Not Detected	
1	Rongelap	238	R27	-5220	-3480	64000	3800	25	300	19	530	48	Not Detected	
1	Rongelap	239				42000	2700	16						
1	Rongelap	240				33000	2300	13						
1	Rongelap	241				22000	1700	8.4						
1	Rongelap	242				51000	2900	20						
1	Rongelap	243				79000	4400	30						
1	Rongelap	244				22000	1400	8.6						
1	Rongelap	245				39000	2300	15						
1	Rongelap	246				37000	2300	14						
1	Rongelap	247				28000	1700	11						
1	Rongelap	248				15000	930	5.6						
1	Rongelap	249				51000	3000	20						
1	Rongelap	250				30000	1800	12						
2	Bokujarito	98				1500	180	0.56	7.8	1.0			Not Detected	
2	Bokujarito	99				1200	140	0.43	17	2.1			Not Detected	
2	Bokkan	100				15000	1100	5.7	28	3.6			Not Detected	
2	Roggutsu	101				3200	370	1.2	7.1	0.88	6.0	0.83	Not Detected	
3	Busch	62				45000	2700	17						
3	Busch	63				3100	340	1.2	5.1	0.63	0.69	1.4	Not Detected	
3	Busch	102				47000	2800	18	71	8.3	200	18	Not Detected	
3	Busch	103				8100	750	3.1	26	3.0	52	4.0	Not Detected	
3	Busch	104				37000	2300	14	55	5.8	90	9.5	1.7	0.32
3	Busch	105				410	73	0.15	0.55	0.12			Not Detected	
3	Weobiji	106				6700	600	2.5	36	3.9			Not Detected	
3	Weobiji	107				1400	160	0.53	8.1	0.89			Not Detected	
3	Weobiji	108				2200	280	0.81	1.1	0.20			Not Detected	
4	Enialo	109				32000	2200	12	56	6.6			Not Detected	
4	Enialo	110				36000	2200	14	100	12			Not Detected	
4	Enialo	111				3000	310	1.1	73	8.0			Not Detected	
4	Rochi	112												

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate	Y Coordinate	RMI Cs-137 In situ Estimate Bq/m ²	RMI Cs-137 In-situ Estimate Bq/m ² Error	RMI Cs-137 External Dose Rate mrem/y	RMI Am-241 0.5 cm Bq/kg	RMI Am-241 0.5 cm Bq/kg Error	RMI Pu-239,240 0.5 cm Bq/kg	RMI Pu-239,240 0.5 cm Bq/kg Error	RMI Co-60 0.5 cm Bq/kg	RMI Co-60 0.5 cm Bq/kg Error
4	Rochi	113				3800	360	1.4	33	3.9			Not Detected	+/- 1 σ
4	Rochi	114				4300	500	1.6	16	1.9			Not Detected	
4	Rochi	115				2900	300	1.1	6.7	0.78			Not Detected	
5	Bogontorinaai	116				210	52	0.077	5.1	0.70			Not Detected	
5	Bogontorinaai	117				1900	220	0.71	5.9	0.69			Not Detected	
5	Bogontorinaai	118				7100	700	2.7	41	5.0			Not Detected	
6	Erapuotsu	61				60000	3400	23						
6	Eniaetok	119				63000	5000	24	41	5.2	94	9.9	Not Detected	
6	Eniaetok	120				66000	3700	26	48	6.0	99	8.7	Not Detected	
6	Eniaetok	121				77000	4300	30	160	11	290	31	Not Detected	
6	Eniaetok	122				51000	3000	20	81	7.9	170	16	2.2	
6	Eniaetok	123				53000	3100	20	24	3.5	67	5.4	Not Detected	0.42
6	Eniaetok	124				41000	2500	16	35	4.6	27	4.6	Not Detected	
6	Eniaetok	125				70000	4000	27	190	19	260	25	Not Detected	
6	Eniaetok	126				10000	870	3.9	19	2.1	40	3.8	Not Detected	
6	Eniaetok	127				99000	5400	38	160	16	360	36	3.1	0.63
6	Eniaetok	128				110000	6100	44	280	27	570	72	5.3	0.93
6	Eniaetok	129				36000	2200	14	84	7.8	180	14	1.4	0.24
6	Eniaetok	130				94000	5200	36	370	21	460	46	Not Detected	
6	Eniaetok	131				60000	3400	23	120	14	170	19	Not Detected	
6	Eniaetok	132				52000	3000	20	210	24	360	34	Not Detected	1.3
6	Eniaetok	133				45000	2700	17	280	27	440	46	3.3	
6	Eniaetok	134				13000	1000	5.0	18	1.8			Not Detected	
6	Eniaetok	135				79000	4400	31	160	18	250	25	Not Detected	
6	Eniaetok	136				38000	2300	14	180	17	97	6.8	2.4	0.60
6	Eniaetok	137				59000	3300	22	93	9.8	200	14	Not Detected	
6	Eniaetok	138				110000	5900	42	370	37	680	66	Not Detected	
6	Erapuotsu	139				66000	3700	25	250	23			5.0	0.98
6	Erapuotsu	140				56000	3200	22	180	10			Not Detected	
16	Eniran	59				36000	2200	14						
16	Burokku	64				56000	3200	22	100	11	200	23	1.6	1.1
16	Burokku	65				18000	1300	6.8	36	4.6			Not Detected	
16	Burokku	66				78000	4300	30	400	41	580	74	Not Detected	
16	Burokku	67				76000	4200	29	60	7.9	110	6.3	Not Detected	
16	Burokku	68				36000	2200	14	79	8.4	220	14	Not Detected	
16	Burokku	69				27000	1800	10	140	16	250	44	Not Detected	
16	Tufa	70				28000	1800	10	39	5.1	80	8.7	Not Detected	
16	Tufa	71				36000	2300	14	150	19	63	10	Not Detected	

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map #	Island	Sample #	Grid #	X Coordinate	Y Coordinate	RMI Cs-137 In-situ Estimate	RMI Cs-137 In-situ Estimate Bq/m ² Error	RMI Cs-137 External Dose Rate	RMI Am-241 0-5 cm	RMI Am-241 0-5 cm Bq/kg Error	RMI Pu-239,240 0-5 cm	RMI Pu-239,240 0-5 cm Bq/kg Error	RMI Co-60 0-5 cm	RMI Co-60 0-5 cm Bq/kg Error
				Meters	Meters	Bq/m ²	+/- 1 σ	mrem/y	Bq/kg	+/- 1 σ	Bq/kg	+/- 1 σ	Bq/kg	+/- 1 σ
16	Tufa	72				4800	530	1.8	240	14	510	42	Not Detected	
16	Tufa	73				18000	1300	7.1	29	3.4	67	5.1	Not Detected	
16	Tufa	74				46000	2800	18	100	13	170	14	Not Detected	
16	Tufa	75				14000	1100	5.4	86	10	170	15	Not Detected	
16	Tufa	76				7200	700	2.7	Not Detected				Not Detected	
16	Tufa	77				37000	2300	14	70	8.4	200	19	Not Detected	
16	Tufa	78				41000	2400	16	95	11	170	13	Not Detected	
16	Tufa	79				43000	2600	17	68	7.8	210	26	Not Detected	
16	Tufa	80				65000	3700	25	78	9.7	290	25	Not Detected	
16	Tufa	81				10000	880	3.9	14	1.7			Not Detected	
16	Eniran	82				20000	1400	7.4	28	3.7	69	5.3	Not Detected	
16	Eniran	83				16000	930	6.2	40	5.0			Not Detected	
16	Eniran	84				11000	640	4.3	52	6.1	100	9.5	Not Detected	
16	Eniran	85				320	69	0.12	2.0	0.28	7.9	30	Not Detected	
16	Eniran	86				990	98	0.37	13	1.5			Not Detected	
16	Eniran	87				9600	620	3.6	100	12	250	18	Not Detected	
17	Arbar	60				15000	1100	5.7						
17	Arbar	88				11000	900	4.2	20	2.6			Not Detected	
17	Arbar	89				36000	2200	14	95	11			Not Detected	
17	Arbar	90				28000	1800	11	110	9.2			Not Detected	
17	Arbar	91				28000	1800	11	43	5.3			Not Detected	
17	Arbar	92				14000	1100	5.4						

Table 1. RMI Nationwide Radiological Study. Radiological measurement data for soils on islands of Rongelap Atoll.

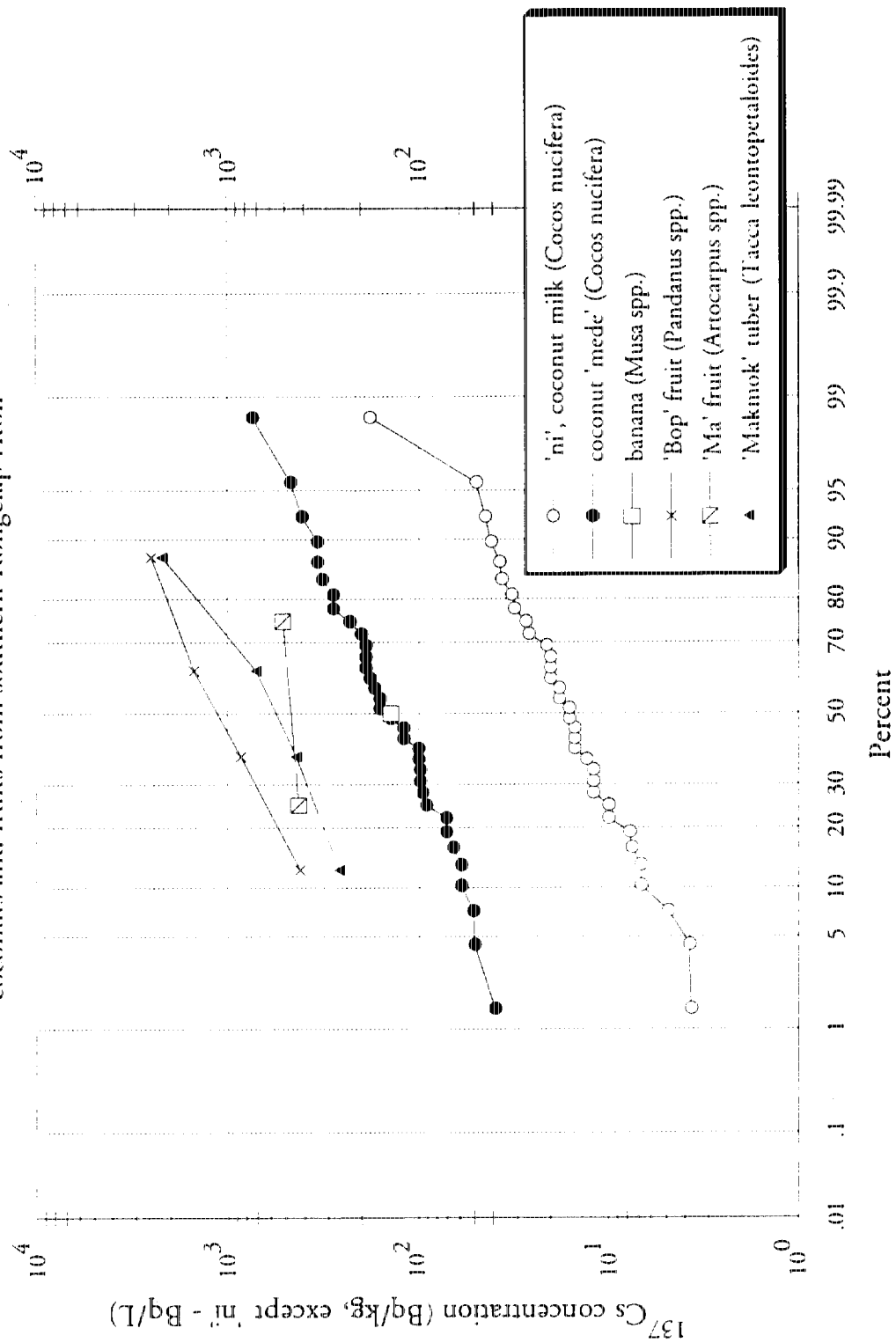
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Map #	Island	Sample #	RMI Cesium-137 Coconut Milk (Cocos nucifera)	RMI Cesium-137 Coconut Milk (Cocos nucifera) Bq/L Error	RMI Cesium-137 Coconut Milk (Cocos nucifera) Bq/L	RMI Cesium-137 Coconut Milk (Cocos nucifera) Bq/L Error	RMI Cesium-137 Coconut Milk (Cocos nucifera) Bq/L	RMI Cesium-137 Coconut Milk (Cocos nucifera) Bq/L Error	RMI Cesium-137 Banana (Musa spp.) Bq/kg	RMI Cesium-137 Banana (Musa spp.) Bq/kg Error	RMI Cesium-137 Bop Fruit (Pandanus spp.) Bq/kg (dry)	RMI Cesium-137 Bop Fruit (Pandanus spp.) Bq/kg Error	RMI Cesium-137 Ma Fruit (Antocarpus spp.) Bq/kg (dry)	RMI Cesium-137 Ma Fruit (Antocarpus spp.) Bq/kg Error	RMI Cesium-137 Ma Fruit (Tacca leontopetaloides) Bq/kg (dry)	RMI Cesium-137 Ma Fruit (Tacca leontopetaloides) Bq/kg Error
1	Rongelap	2		1.1	100	7.8	85	5.5								
1	Rongelap	4		0.53	160	8.0	43	4.6			1500	54			710	44
1	Rongelap	4														
1	Rongelap	6		0.93	190	12	77	4.9					428	26		
1	Rongelap	8														
1	Rongelap	15			740	42	140	8.8								
1	Rongelap	18		1.4	65	3.9	130	1.5								
1	Rongelap	19		0.26					140	10			514	24		
1	Rongelap	19														
1	Rongelap	22														
1	Rongelap	25														
1	Rongelap	29		1.4	180	12	30	2.0								
1	Rongelap	29		0.32	39	3.4	66	4.2								
1	Rongelap	49		0.48	140	9.7	160	10								
1	Rongelap	51		1.0	170	13	100	6.4								
1	Rongelap	189			98	5.1	42	2.5								
1	Rongelap	191		2.3	98	6.5	72	4.2								
1	Rongelap	194			98											
1	Rongelap	196														
1	Rongelap	199		1.5	340	28	110	5.8								
1	Rongelap	205		0.68	320	20	180	11								
1	Rongelap	210		1.7	180	11	330	19								
1	Rongelap	13		0.76	180	16										
1	Rongelap	26		1.3	280	13										
3	Busch	62		2.1	51	5.1	150	9.9								
3	Busch	103		1.1	160	14	300	19								
3	Busch	103		0.64	230	20	270	17								
4	Enlato	110		1.3	59	5.6	14	1.6								
4	Enlato	111		2.0	95	5.3	74	7.9								
6	Erapuotsu	61		2.6	470	28	280	29								
6	Erapuotsu	121		1.1	120	12	110	12				94				
6	Erapuotsu	130		8.5	410	36	160	10			2500					
6	Erapuotsu	135		1.4	71	6.5	250	16								
6	Erapuotsu	140		0.90	280	23	430	46								
15	Buroku	65		1.2	71	5.5	200	13								
15	Buroku	67		0.83	50	4.2	150	9.5								
17	Tufa	73		0.85	120	9.0	88	9.4								
17	Tufa	81		0.24	59	4.8										
17	Eniran	82		1.1	200	16	120	13								
17	Eniran	86		0.45	91	7.6	49	4.9								
18	Arbar	90		0.64	340	30	120	13								
18	Arbar	90			100	8.7	64	6.9			420	19				
18	Arbar	91		0.47												

Table 2. RMI Nationwide Radiological Study. Radiological measurement data for coconuts and fruits on islands of Rongelap Atoll.

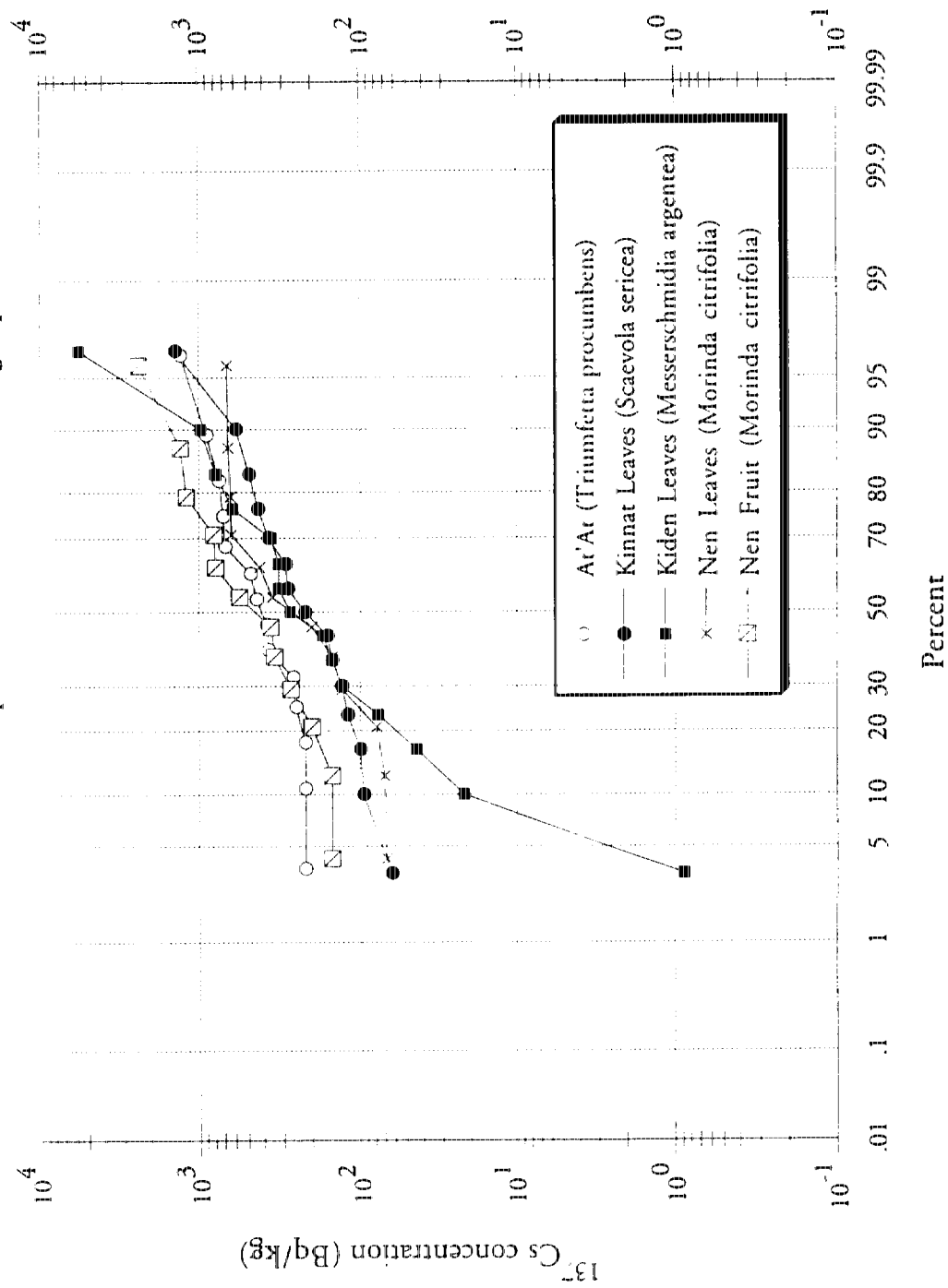
1	2	3	4	5	6	7	8	9	10	11	12	13
Map #	Island	Sample #	RMI Cesium-137 ATAI (Triumfetta procumbens)	RMI Cesium-137 ATAI (Triumfetta procumbens) Bq/kg (dry) Error +/- 1 σ	RMI Cesium-137 Kinnat Leaves (Scaevola senecae) Bq/kg (dry)	RMI Cesium-137 Kinnat Leaves (Scaevola senecae) Bq/kg (dry) Error +/- 1 σ	RMI Cesium-137 Kiden Leaves (Messerschmidia argentea) Bq/kg (dry)	RMI Cesium-137 Kiden Leaves (Messerschmidia argentea) Bq/kg (dry) Error +/- 1 σ	RMI Cesium-137 Nen Leaves (Morinda citrifolia) Bq/kg (dry)	RMI Cesium-137 Nen Leaves (Morinda citrifolia) Bq/kg (dry) Error +/- 1 σ	RMI Cesium-137 Nen Fruit (Morinda citrifolia) Bq/kg (dry)	RMI Cesium-137 Nen Fruit (Morinda citrifolia) Bq/kg (dry) Error +/- 1 σ
1	Rongelap	2			100	5.4	150	5.4				
1	Rongelap	2										
1	Rongelap	4	710	15								
1	Rongelap	8	220	5.8			320	7.7				
1	Rongelap	8					5700	66				
1	Rongelap	9										
1	Rongelap	18										
1	Rongelap	22										
1	Rongelap	22										
1	Rongelap	22	480	10			790	16				
1	Rongelap	22										
1	Rongelap	22										
1	Rongelap	22										
1	Rongelap	24			280	10						
1	Rongelap	24			130	4.5						
1	Rongelap	25			490	17						
1	Rongelap	25										
1	Rongelap	40			590	16						
1	Rongelap	40					970	21				
1	Rongelap	49										
1	Rongelap	49										
1	Rongelap	50										
1	Rongelap	50	250	6.2								
1	Rongelap	55										
1	Rongelap	55	1300	20								
1	Rongelap	55			370	10						
1	Rongelap	56										
1	Rongelap	56	220	9.8								
1	Rongelap	56	750	19								
1	Rongelap	56										
2	Bokujanto	98	260	8.0								
3	Busch	62										
3	Busch	62			430	9.8						
3	Busch	102					360	7.0				
3	Busch	103			290	19						
3	Busch	103										
3	Busch	103					270	7.8				
3	Wobijij	108					320	2.3				
4	Enatio	110					44	4.8				
5	Rochi	113					170					
5	Rochi	114										
5	Rochi	114										
6	Enaetok	130			1400	20						
6	Erapuotsu	61										
6	Erapuotsu	61	900	43			670	32				
6	Erapuotsu	140			120	6.4						
17	Eniran	59			150	9.6						
17	Eniran	59					22	0.64				
17	Eniran	59	440	22								
17	Tufa	72			95	5.2						
17	Tufa	78										
17	Tufa	81	220	10								
17	Eniran	82										
17	Eniran	82	370	13								
17	Eniran	84										
17	Eniran	86	380	8.7								
17	Eniran	86					130	6.2				
17	Eniran	87					77	4.6				
17	Eniran	87										
18	Arbar	60			220	6.1						
18	Arbar	91			63	3.4						
18	Arbar	92	690	31								
18	Arbar	92					620	13				
18	Arbar	92			160	8.4						

Table 3. RMI Nationwide Radiological Study. Radiological measurement data for medicinal plants on islands of Rongelap Atoll.

Probability plot of ^{137}Cs measurement data of
coconuts and fruits from southern Rongelap Atoll



Probability plot of ^{137}Cs measurement data of
traditional medicinal plants from southern Rongelap Atoll



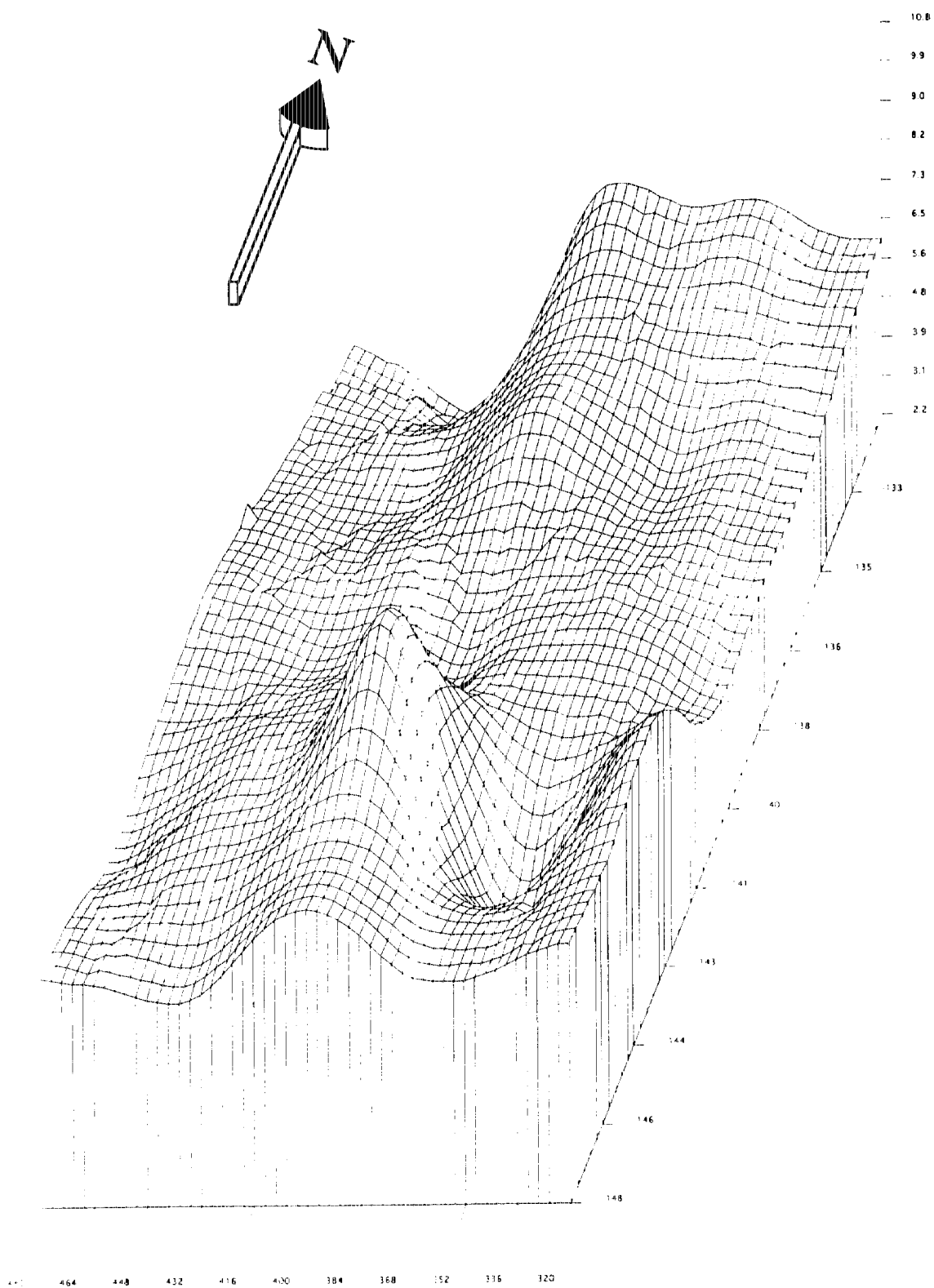
Small Grid Interpolation Maps

The following 12 maps display smooth interpolations of the radiological measurements taken from the 4 small sampling grids on Rongelap Island (H2, J3, R27 and Q29). Each of the four cells (200 m x 200 m each) were sampled on a 40 m x 40 m grid (25 samples per grid). Three types of data are displayed for each grid: in-situ spectrometry net count-rate for ^{137}Cs (c/s), ^{137}Cs concentration in surface soil (0-5 cm depth) measured in the laboratory from a soil sample, and the combined concentration of $^{239+240}\text{Pu}$ plus ^{241}Am , measured in the laboratory from the same surface soil sample as the cesium.

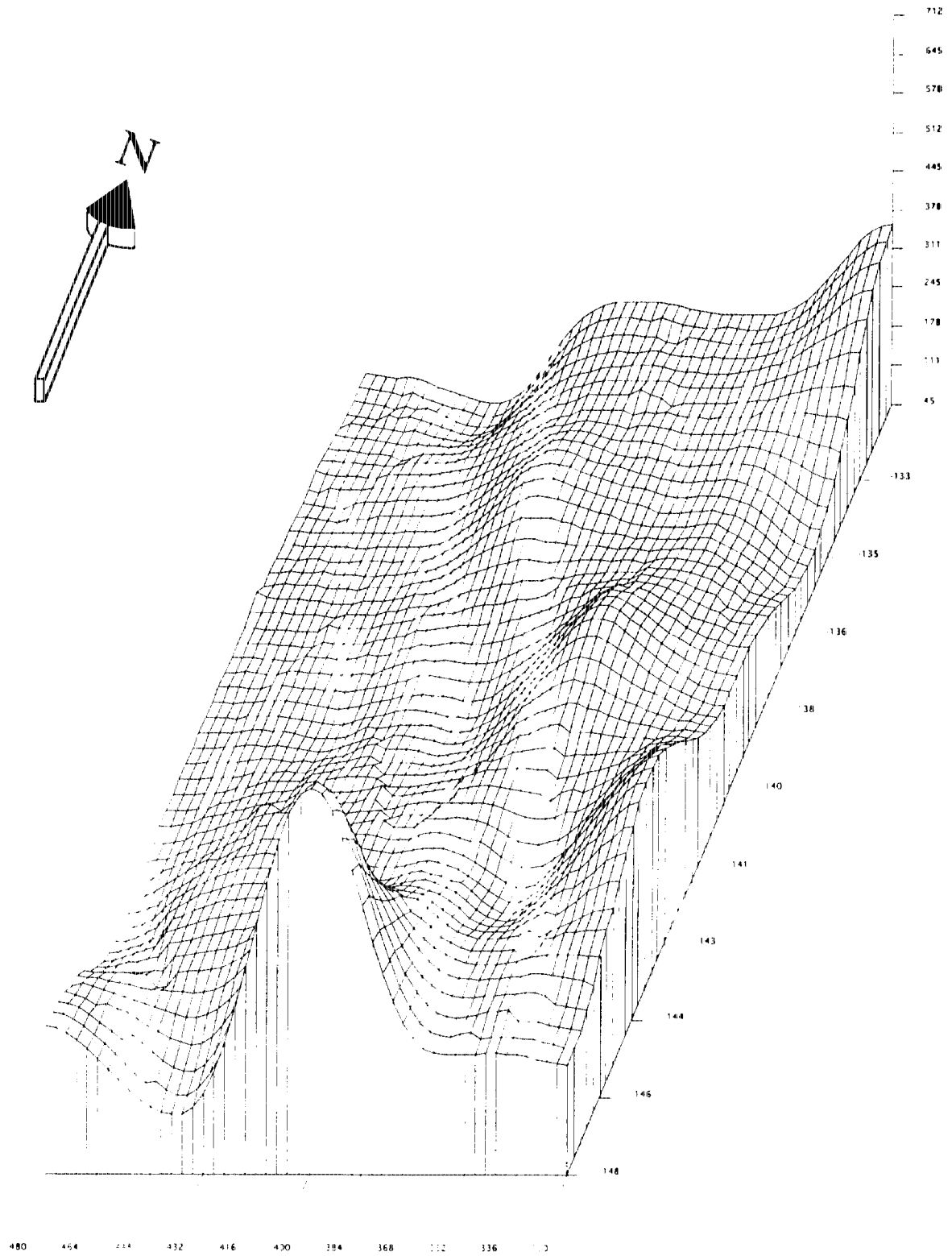
The interpolation maps were constructed using MacGRIDZØ™ software, Version 3.33 (Rockware, Inc., Wheat Ridge, CO). The 5 x 5 data array of each cell was interpolated to a 50 x 50 array using a "moving weighted least-squares" algorithm, with a radial search from each point, up to 2 points distance. Neighboring data points are weighted according to the inverse of their distance from the grid node. A regional polynomial is applied to the grid model to smooth the surface. The order of the polynomial is automatically set by the software up to order six.

The interpolation maps are intended only for a visualization of the spatial variation of the measurement data. Detailed analytical analysis of spatial variation is presented in the next section: "Geostatistical Analysis of Radionuclides on Rongelap Island" by Diggle, Harper and Tawn of the University of Lancaster.

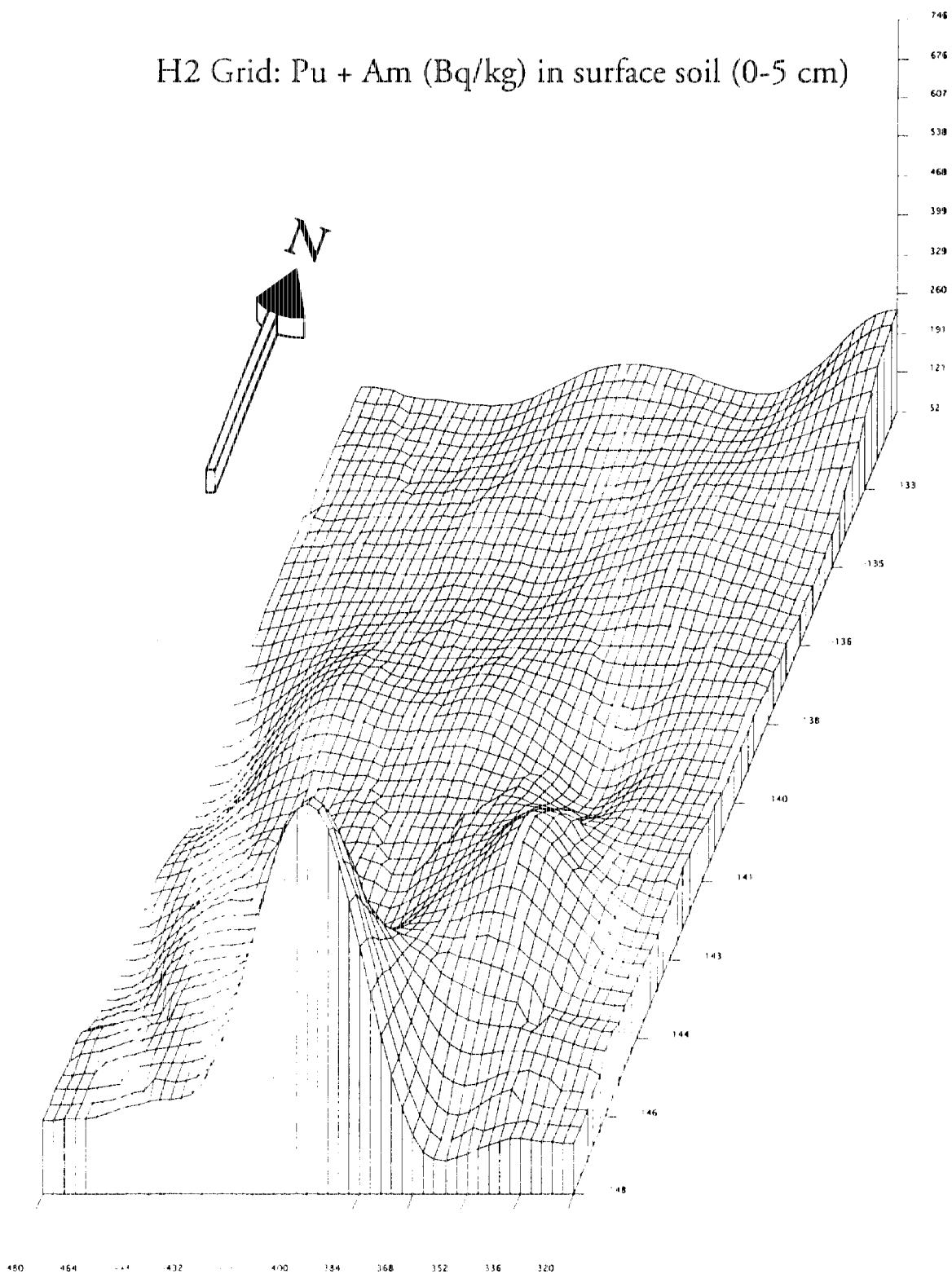
H2 Grid: Cs-137 measurements (c/s)



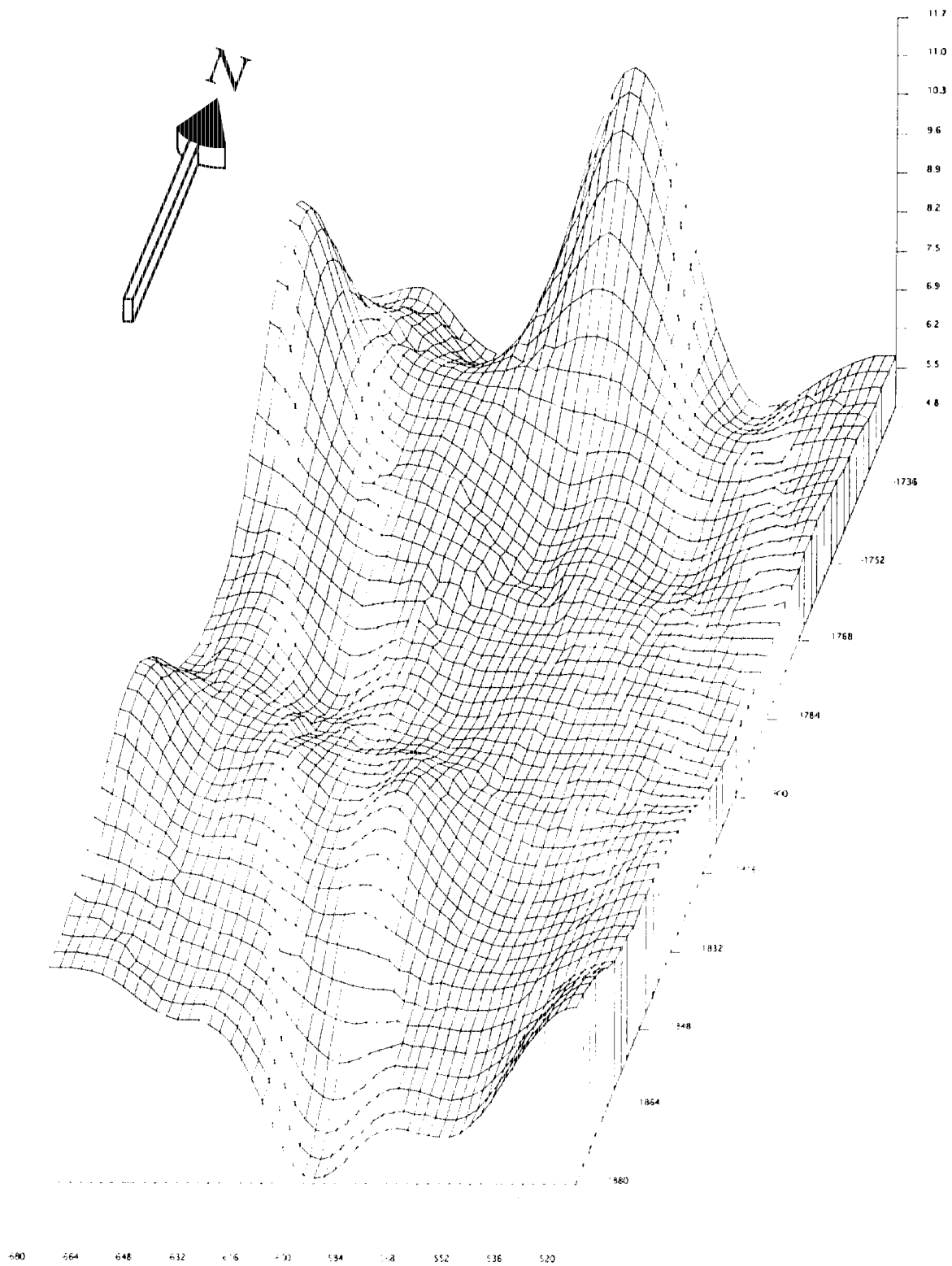
H2: Cs-137 (Bq/kg) in surface soil (0-5 cm)



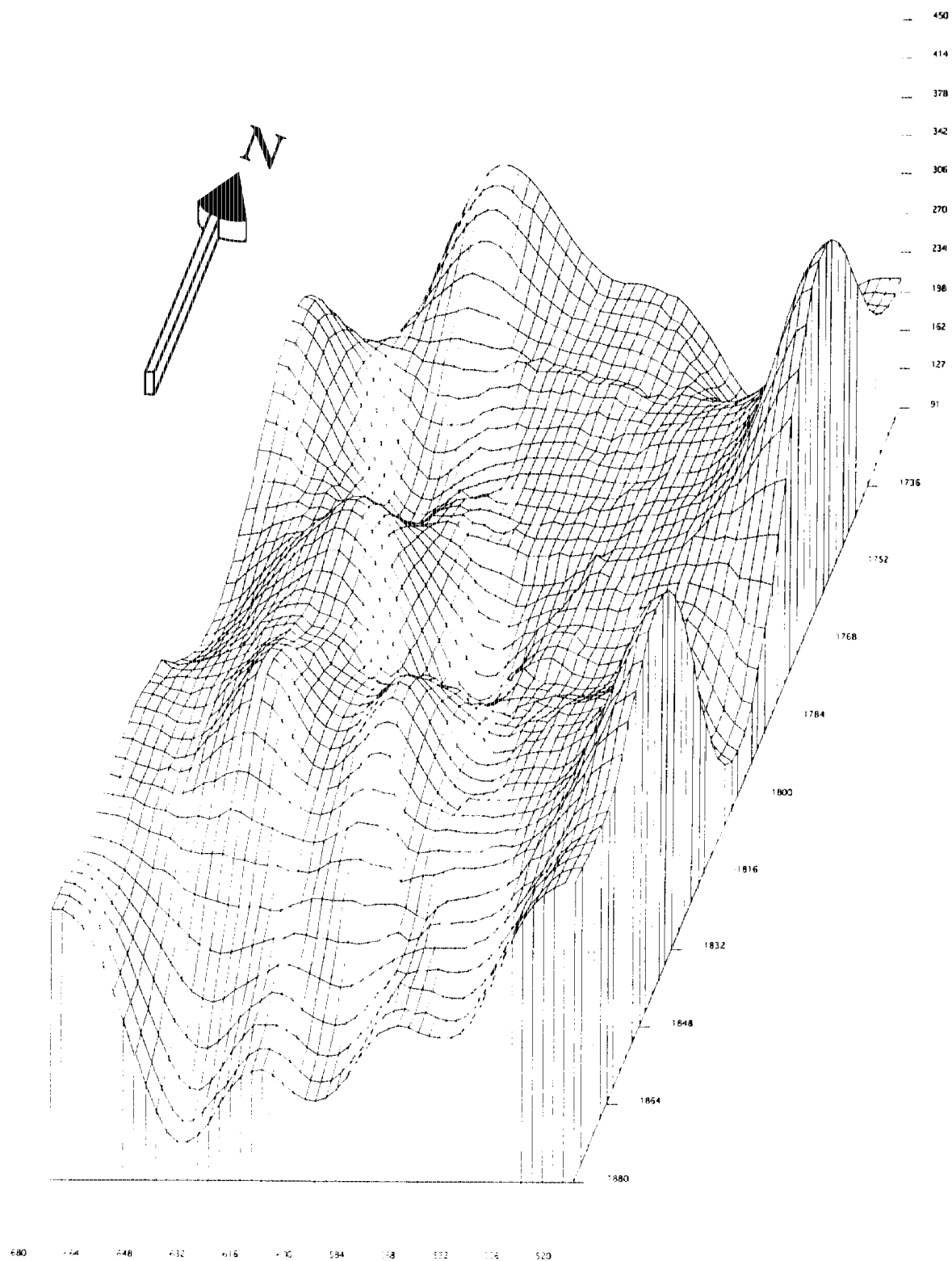
H2 Grid: Pu + Am (Bq/kg) in surface soil (0-5 cm)



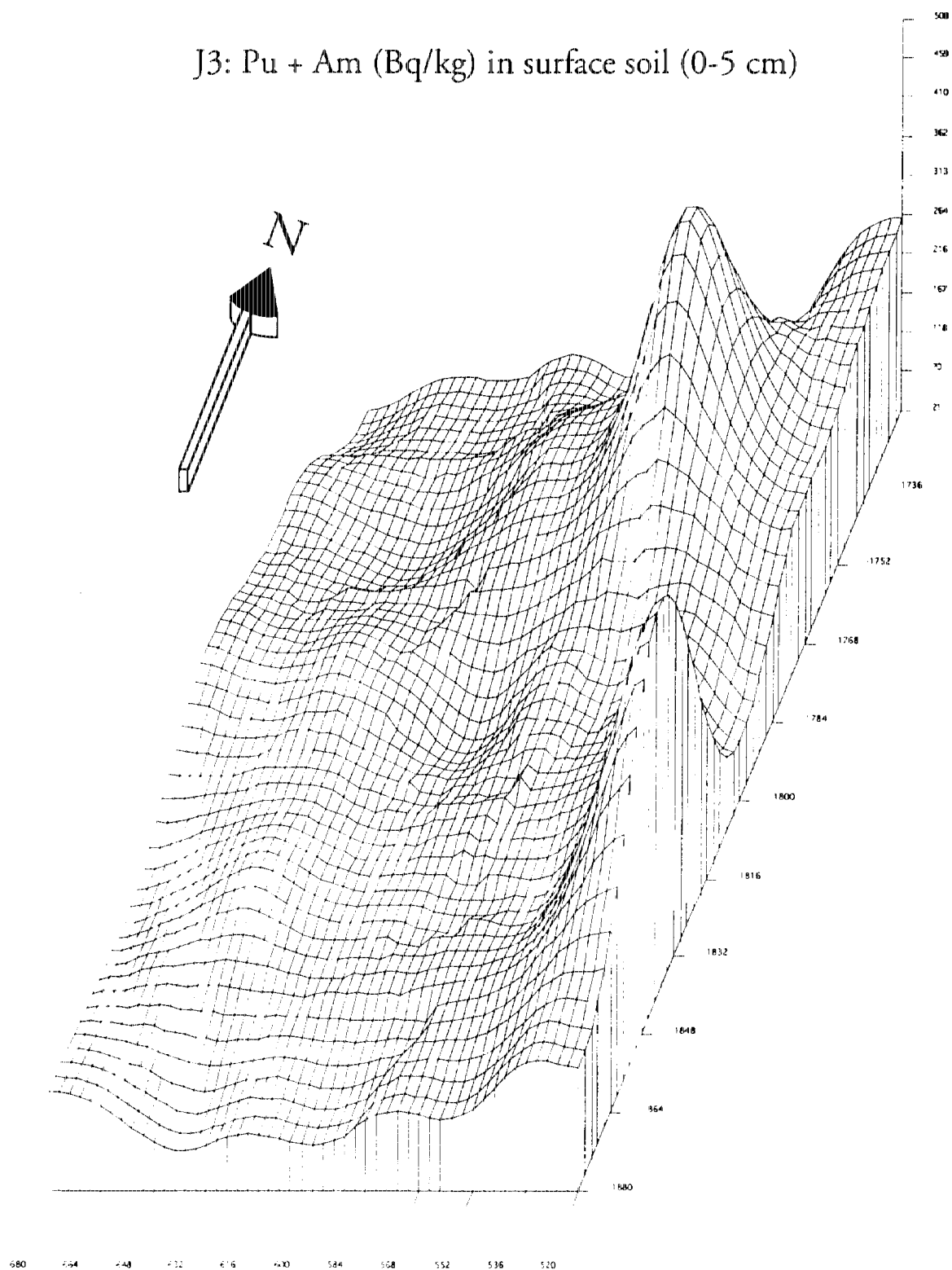
J3: Cs-137 in-situ spectrometry measurements (c/s)



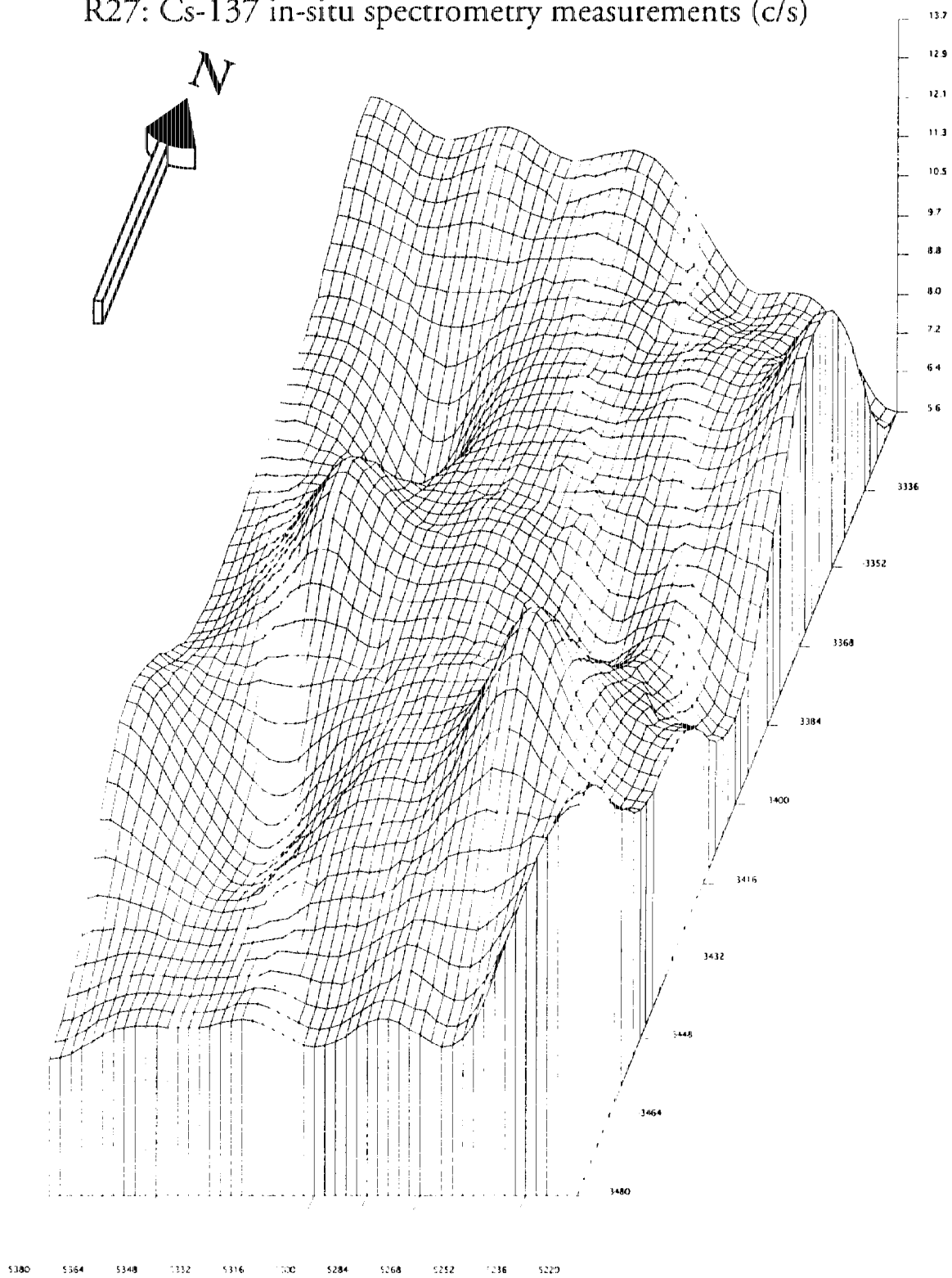
J3: Cs-137 (Bq/kg) in surface soil (Bq/kg)



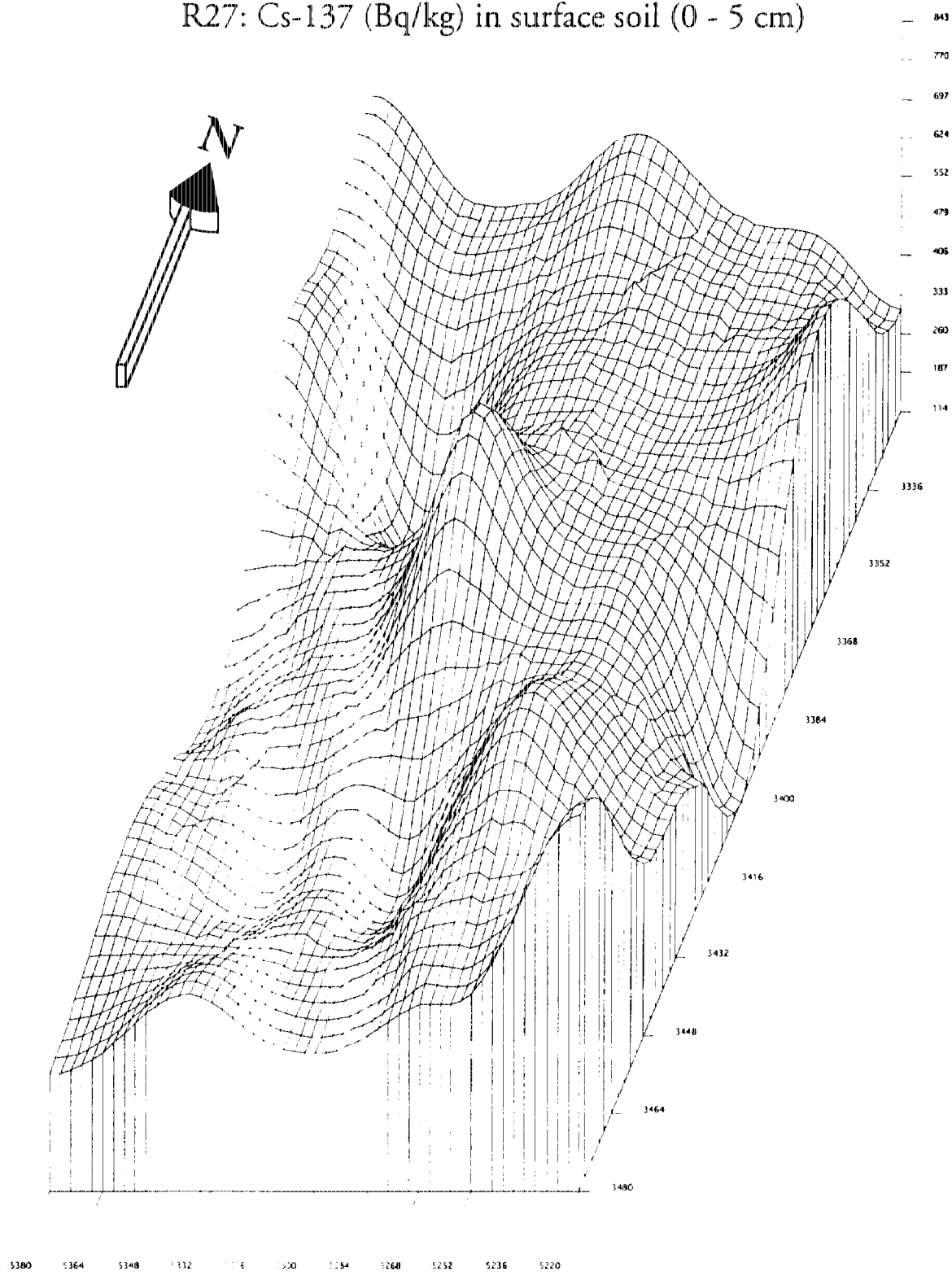
J3: Pu + Am (Bq/kg) in surface soil (0-5 cm)



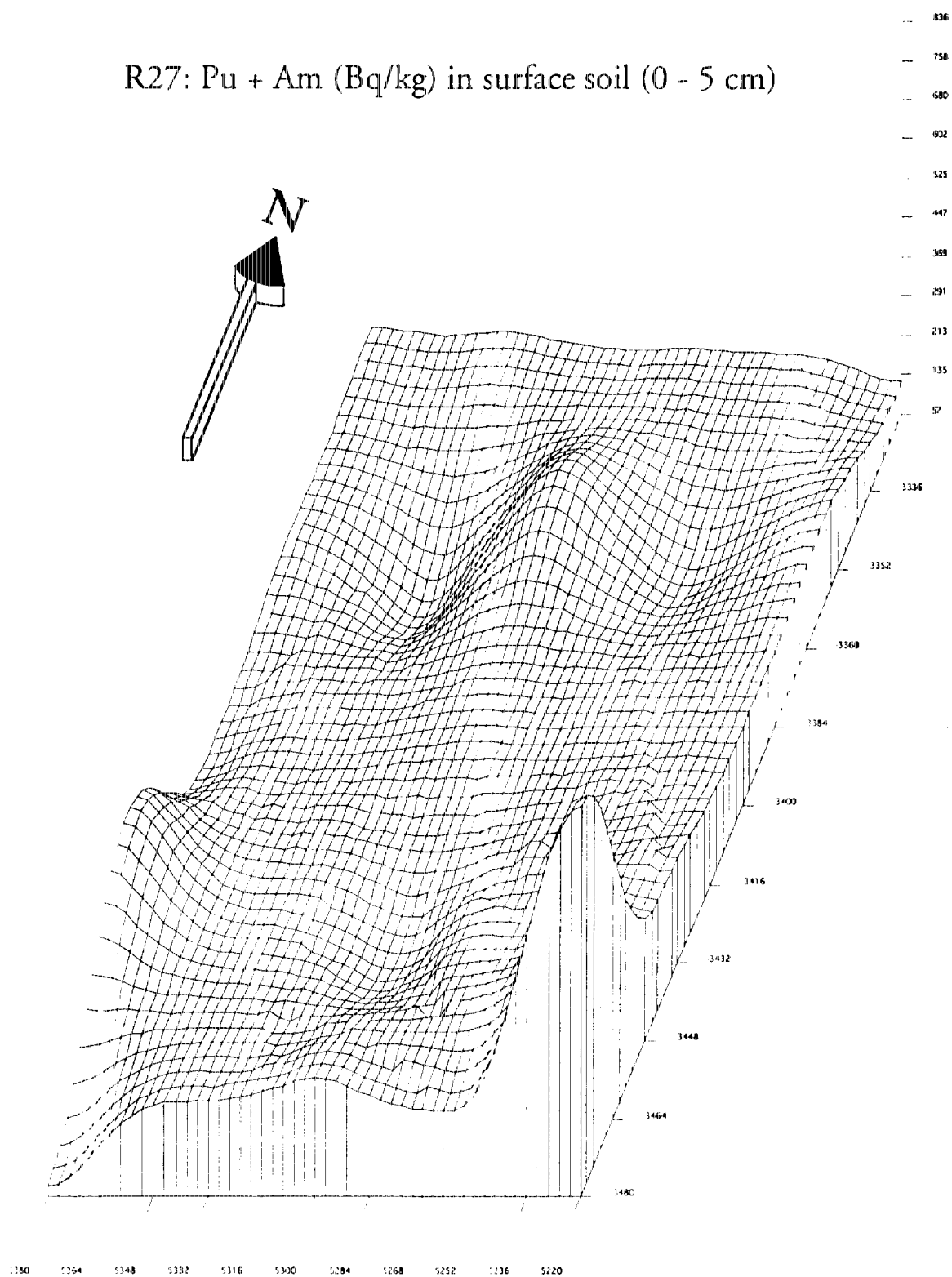
R27: Cs-137 in-situ spectrometry measurements (c/s)



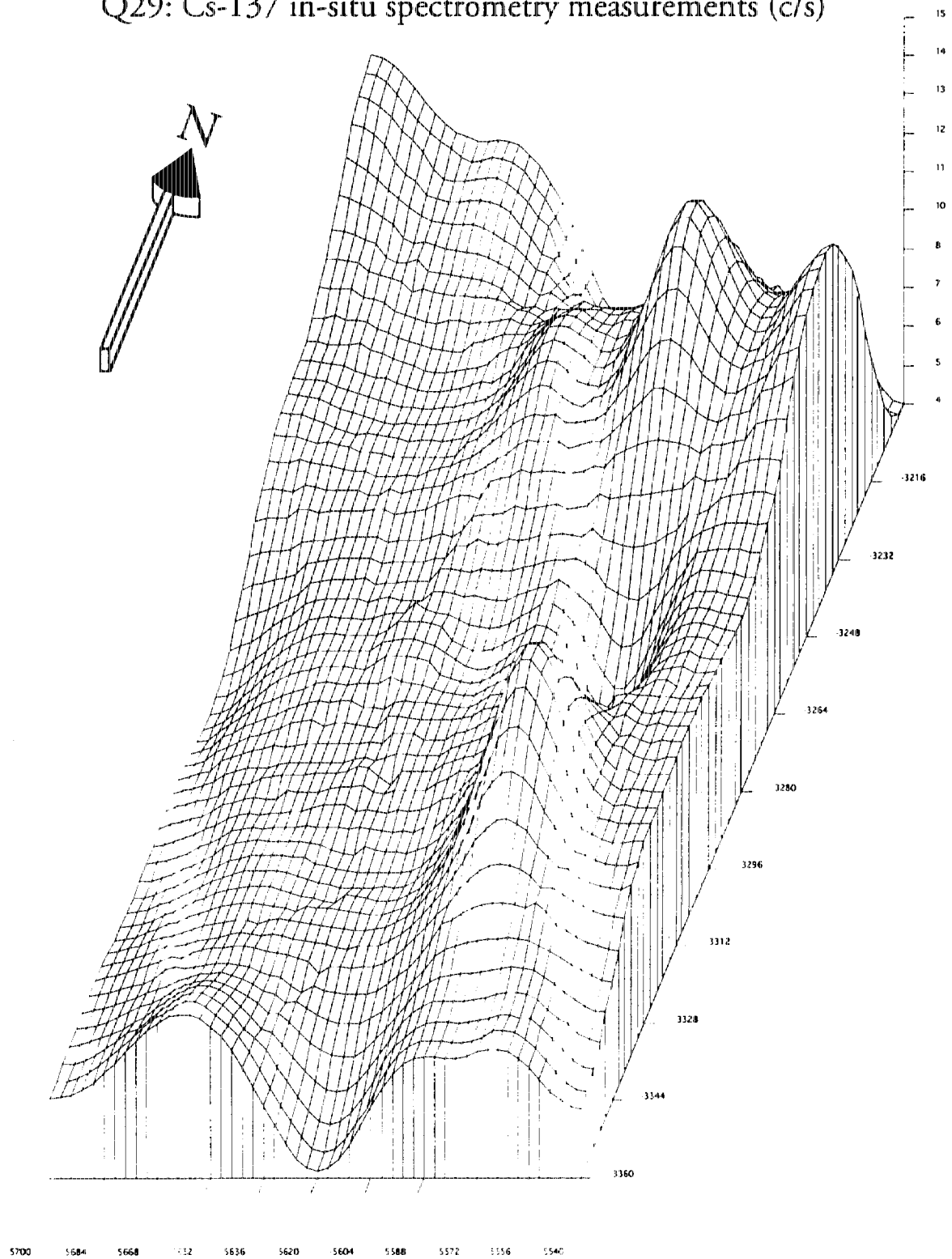
R27: Cs-137 (Bq/kg) in surface soil (0 - 5 cm)



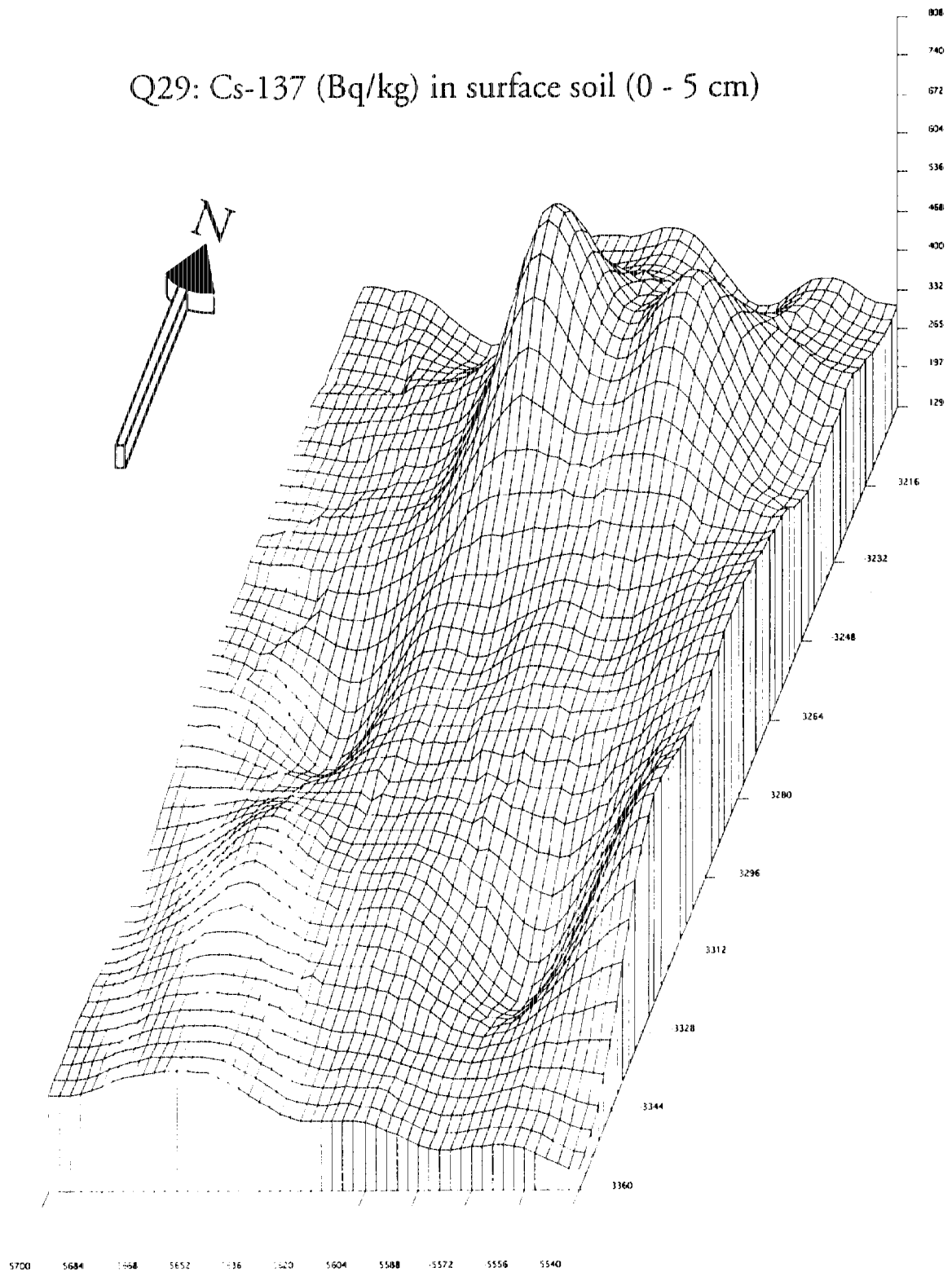
R27: Pu + Am (Bq/kg) in surface soil (0 - 5 cm)



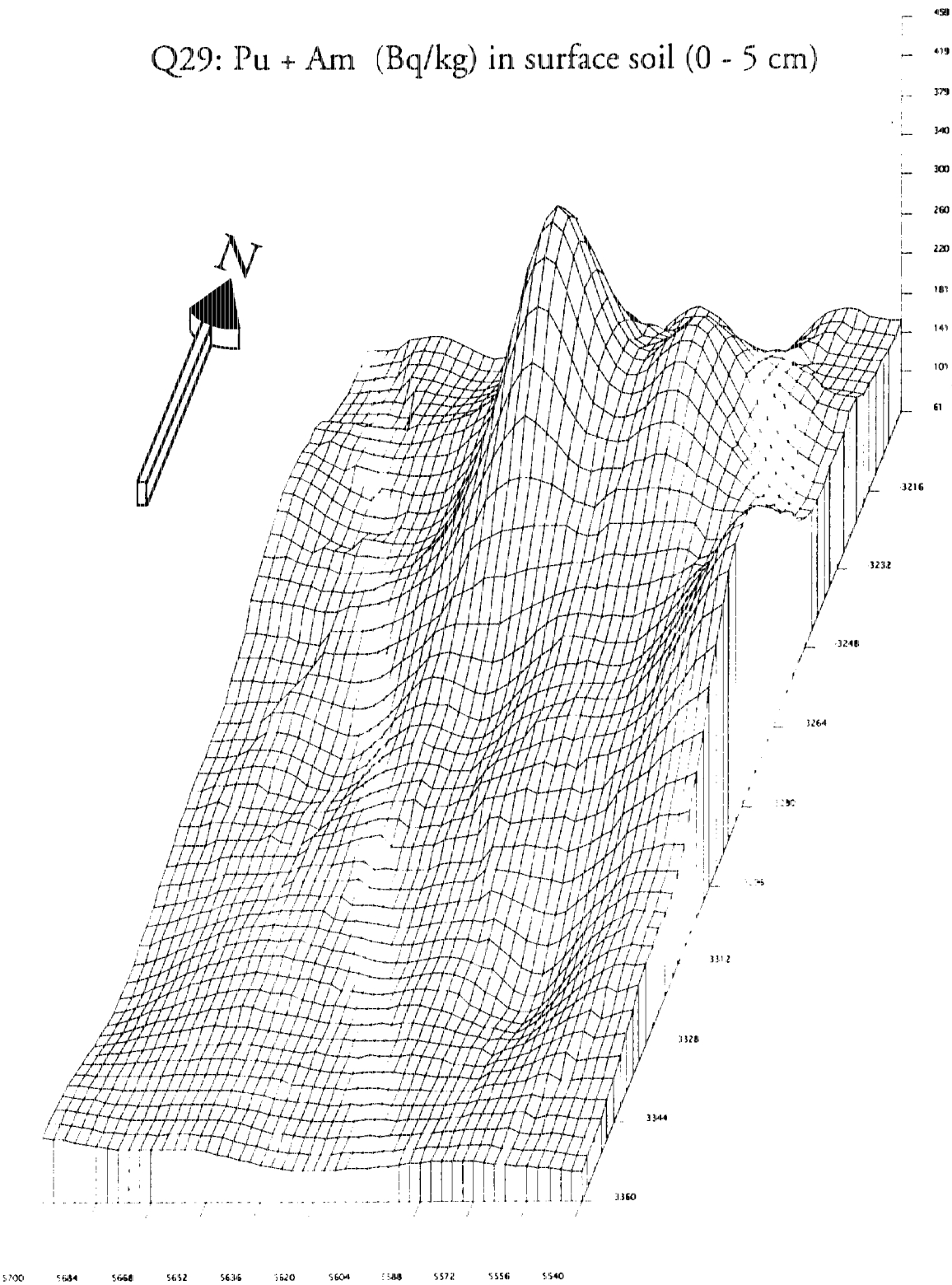
Q29: Cs-137 in-situ spectrometry measurements (c/s)



Q29: Cs-137 (Bq/kg) in surface soil (0 - 5 cm)



Q29: Pu + Am (Bq/kg) in surface soil (0 - 5 cm)



APPENDIX 4

STUDY OF TRADITIONAL OR "LOCAL FOOD ONLY" DIET EXECUTIVE SUMMARY

Bernd Franke
Institute for Energy and Environmental Research

November 1994

Geostatistical Analysis of Radionuclides on Rongelap Island

Peter Diggle, Louise Harper and Jonathan Tawn
(Department of Mathematics and Statistics, Lancaster University)

September 6, 1994

1 Introduction

The criterion for Rongelap Island to be of habitable condition is expressed in terms of the maximum permitted concentrations of radionuclides at any point on the island. It is clearly impossible to make direct measurements at every point on the island. However, it is possible (and desirable) to use direct measurements at a finite set of sample locations to obtain estimates of the levels of pollutant concentrations at any point on the island, and to use the resulting estimated map to identify regions of the island where maximal concentrations are likely to be found.

The approach taken in this report is the following:

- (i) to investigate the nature of the spatial dependence present in the observed data, and to formulate a model to describe this;
- (ii) to use this model to predict values of each isotope over the island and to display the spatial variation graphically.

1.1 Notes on the Data and Notation

The data analysed in this report consist of field measurements of local concentrations of caesium(Cs), and lab measurements of americium(Am) and plutonium(Pu). Separate analyses are performed on Cs and on the sum of Am plus Pu. Initial measurements were taken at 63 sample locations on an approximate 200x200 metre grid covering the island - the sample locations are not exactly at the centre of the grid cells, due to practical constraints. These data were later supplemented by dividing four of the original grid squares into finer grids of 40m spacing, and taking an additional 25 measurements within each fine grid cell. This provided a further 98 measurements in all, for each isotope; measurements were not made at two of the locations within the small grid square H2 which extended beyond the shore of the island. Figure 0 gives a map of the island with the sample locations marked as solid dots. The sample locations are recorded accurately, but the coast-line is an approximation based on a manual digitisation, hence the apparent location of some samples off-shore!

1.2 Assumptions

In order to develop a model for the spatial variation in the data, we make the following assumptions.

- (i) The values recorded at each location are subject to measurement error, i.e the measurement process is such that if the concentration at a particular location were measured again, a different observed value would be obtained.
- (ii) For each isotope, the data, $Z_i = Z(x_i) : i = 1, \dots, 161$, form a partial realisation of a stationary stochastic process $\{Z(x) : x \in R^2\}$, of the form

$$Z(x_i) = S(x_i) + N_i \quad : \quad N_i \sim N(0, \tau^2), \quad (1)$$

i.e the $Z(\cdot)$ process is composed of an underlying process $S(\cdot)$, which represents the true concentration, plus a component of random variation represented by the N_i .

- (iii) The correlation structure of $S(\cdot)$ depends only on the distance between (and not on the orientation of) the data points, so that $\text{Cov}\{S(x), S(y)\} = \sigma^2 \rho(\|x - y\|)$, where σ^2 is the variance of $S(\cdot)$, $\rho(\cdot)$ the correlation function of $S(\cdot)$ and $\|\cdot\|$ denotes Euclidean distance.

One assumption in the above is that the variance of the measurement is independent of the true concentration. A more plausible assumption is that the measurement error depends on the concentration. A convenient way to reflect this is to apply the model to log-concentrations, for which the implicit assumption is that the coefficient of variation of the measurement error is independent of the concentration.

2 Investigation of Spatial Dependence

The variogram of a stationary process $\{Z(x) : x \in R^2\}$ is defined by

$$V(h) = \frac{1}{2} E[\{Z(x) - Z(x - h)\}^2], \quad x \in R^2, h \in R^2.$$

Furthermore, if $E[Z(x)] = \mu$ and $\text{Cov}\{Z(x), Z(x - h)\} = \gamma(h)$ then the variogram can be expressed as $V(h) = \gamma(0) - \gamma(h) = \sigma^2\{1 - \rho(h)\}$, where σ^2 is the variance, and $\rho(h)$ the correlation function of $Z(\cdot)$. Because we assume that the correlation between $Z(x)$ and $Z(y)$ depends only on the distance between x and y , we will henceforth treat h as a scalar quantity.

2.1 Estimation of the Variogram

The variogram can be estimated by

$$2\gamma(h) = \{N(h)\}^{-1} \sum \{Z(x_i) - Z(x_j)\}^2 \quad (2)$$

where the summation is over all pairs (x_i, x_j) such that $\|x_i - x_j\| \approx h$, and $N(h)$ is the number of such pairs. In other words, we specify a tolerance interval around h and use those pairs of data values whose separation distances are within that interval to calculate $\gamma(h)$.

2.2 Choice of Variogram Model for the Rongelap data

We aim to choose the simplest model which is consistent with the observed data so as to avoid estimating unnecessary additional parameters, as this would tend to increase the prediction errors.

2.2.1 Correlation Structure

The sample variograms in Figure 1 show that there is evidence of positive spatial dependence in the data. In general, there is an initial increase in $\gamma(h)$ over small distances h , which levels off as h gets larger, i.e the correlation in the data decays as the separation distance increases. We model this decay by the function

$$\rho(h) = \exp(-\alpha h^2). \quad (3)$$

This corresponds to a mean-square differentiable stochastic process, which in turn guarantees that our predicted surface will be smoothly varying over the island. Figure 1 indicates that the model fits the data reasonably well.

2.2.2 A Possible Extension of the Model

A possible extension would be to consider a process $Z(\cdot)$ composed of two independent processes $Z_1(\cdot)$ and $Z_2(\cdot)$, so that for each x we have $Z(x) = Z_1(x) + Z_2(x)$. In this extended model, the processes $Z_1(\cdot)$ and $Z_2(\cdot)$ correspond to small-scale and large-scale spatial variation and have respective variograms

$$\gamma_i(h) = \sigma_i^2 \{1 - \rho_i(h)\}, \quad i = 1, 2$$

Then, the theoretical variogram of the process $Z(\cdot)$ would be

$$\gamma(h) = \gamma_1(h) + \gamma_2(h).$$

Hence, if each of the variograms $\gamma_i(\cdot)$ were of the general form (3), but with different parameter values to reflect their respective small-scale and large-scale behaviour, the variogram $\gamma(\cdot)$ would show an initial increase and levelling out due to the small-scale variation, followed by a second increase and levelling out due to the large-scale variation.

This extension has some intuitive appeal, but there is no indication that it is required to provide a reasonable fit to the Rongelap data

2.2.3 Measurement Error

Recall the assumption (1) that the data arise as realizations from a process which includes a component of measurement error. The variogram of such a process is given by

$$\gamma_2(h) = \gamma_1(h) + \tau^2 \quad (4)$$

where τ^2 is the variance of the measurement error (note that this is a special case of the extended model described in Section 2.2.2). Thus, the variogram of the $Z(\cdot)$ process will

not approach zero as h approaches the origin. It can be seen from Figure 1 that the behaviour of the sample variograms for the Rongelap data is consistent with the inclusion of a measurement error component in the model.

Incidentally, the inclusion of a measurement error component is common in geostatistical work, where it is called the "nugget effect". In practice, this component of variance can be interpreted as a combination of measurement error (which is clearly present in the Rongelap data) and very short-range spatial variation which cannot be identified from the available data (i.e. for the Rongelap data, variation on a scale smaller than 40metres). In principle, the model extension noted above, together with an extended data-base, could resolve this ambiguity of interpretation. Whether this is necessary depends on the precise objectives of the data-analysis. For example, if we wanted to make inferences about the maximum value of $S(x)$ over the island, it would be vital to distinguish measurement error from very short-range variation, whereas if we wanted only to make inferences about the maximum value of a spatial average,

$$T(x) = (\pi r_0^2)^{-1} \int S(x - y) dy, \quad (5)$$

where the integration is over a disc of radius $r_0 > 40$ centred on the point x , the distinction is much less important.

2.3 Variogram Model

We suppose that our data come from a process of the form (1), also that $S(x)$ is a stationary Gaussian process with mean μ , variance σ^2 and variogram $\gamma_s(h) = \sigma^2\{1 - \rho(h)\}$. Incorporating this, and the correlation model (3) into (4) gives the variogram model for the observed data as

$$\gamma_z(h; \theta) = \sigma^2\{1 - \exp(-\alpha h^2)\} + \tau^2 \quad (6)$$

where $\theta = (\sigma^2, \tau^2, \alpha)$. For each isotope, estimates of the parameters θ were obtained using the approximate weighted-least-squares criterion given in Cressie (1985). These estimates are given in Table 1.

Strictly, this model cannot simultaneously fit both the untransformed and the log-transformed concentrations. As always, the model is at best an approximation to the truth. See below for further comments.

2.4 Results

For the Rongelap data, sample variograms, calculated using (2), are shown in Figure 1. The vertical bars on each graph are crude estimates of the standard error of each estimated $\gamma(h)$, and should not be used for formal inference. However, they are qualitatively useful in indicating, for example, that $\gamma(h)$ is generally estimated with decreasing precision as h increases. The fitted variogram models are also shown in Figure 1.

Lognormal predictions for Lab Am+Pu ($r_0=200$)

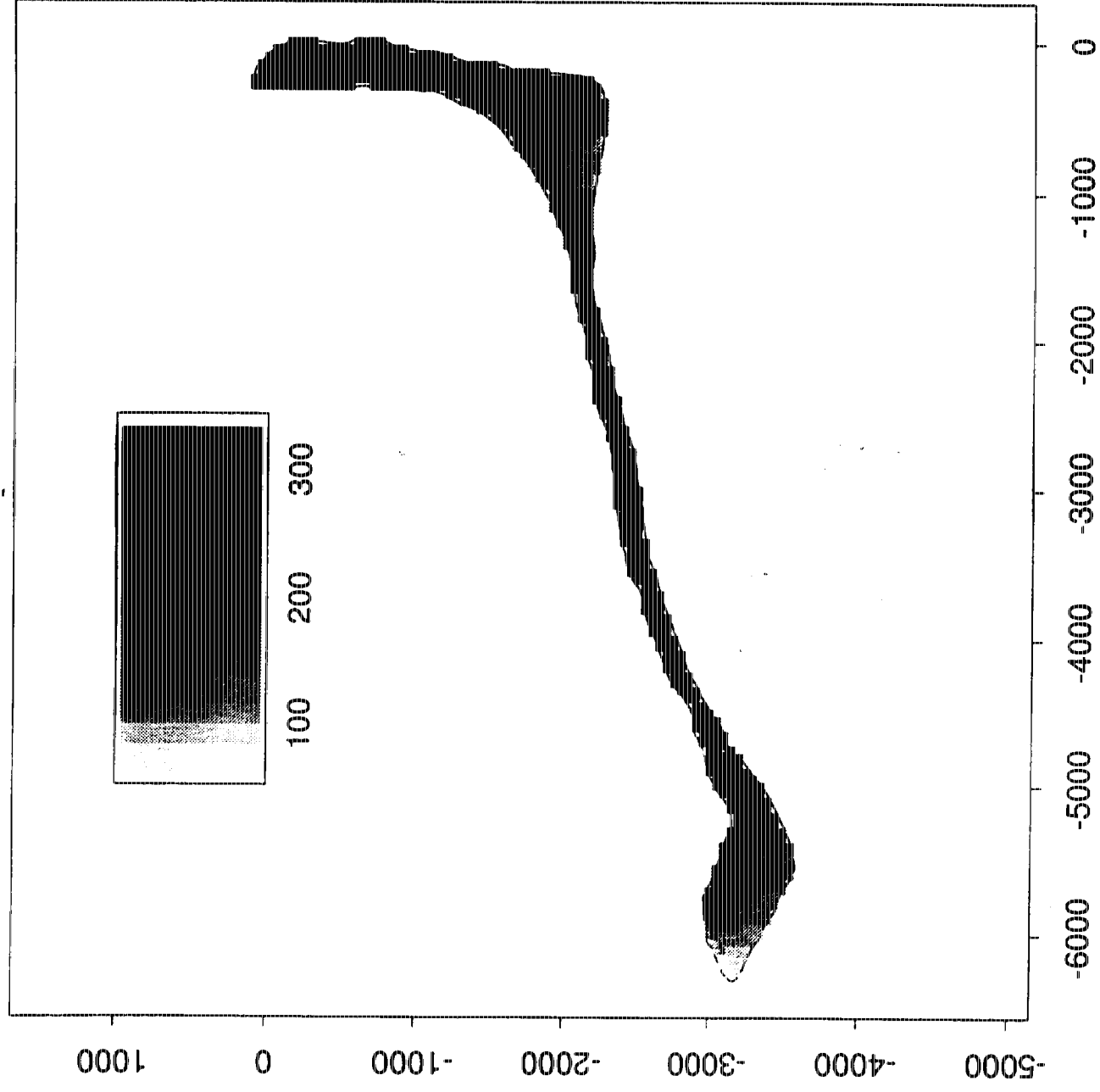


Figure 3i.

Lognormal predictions for Lab Am+Pu ($r_0=500$)

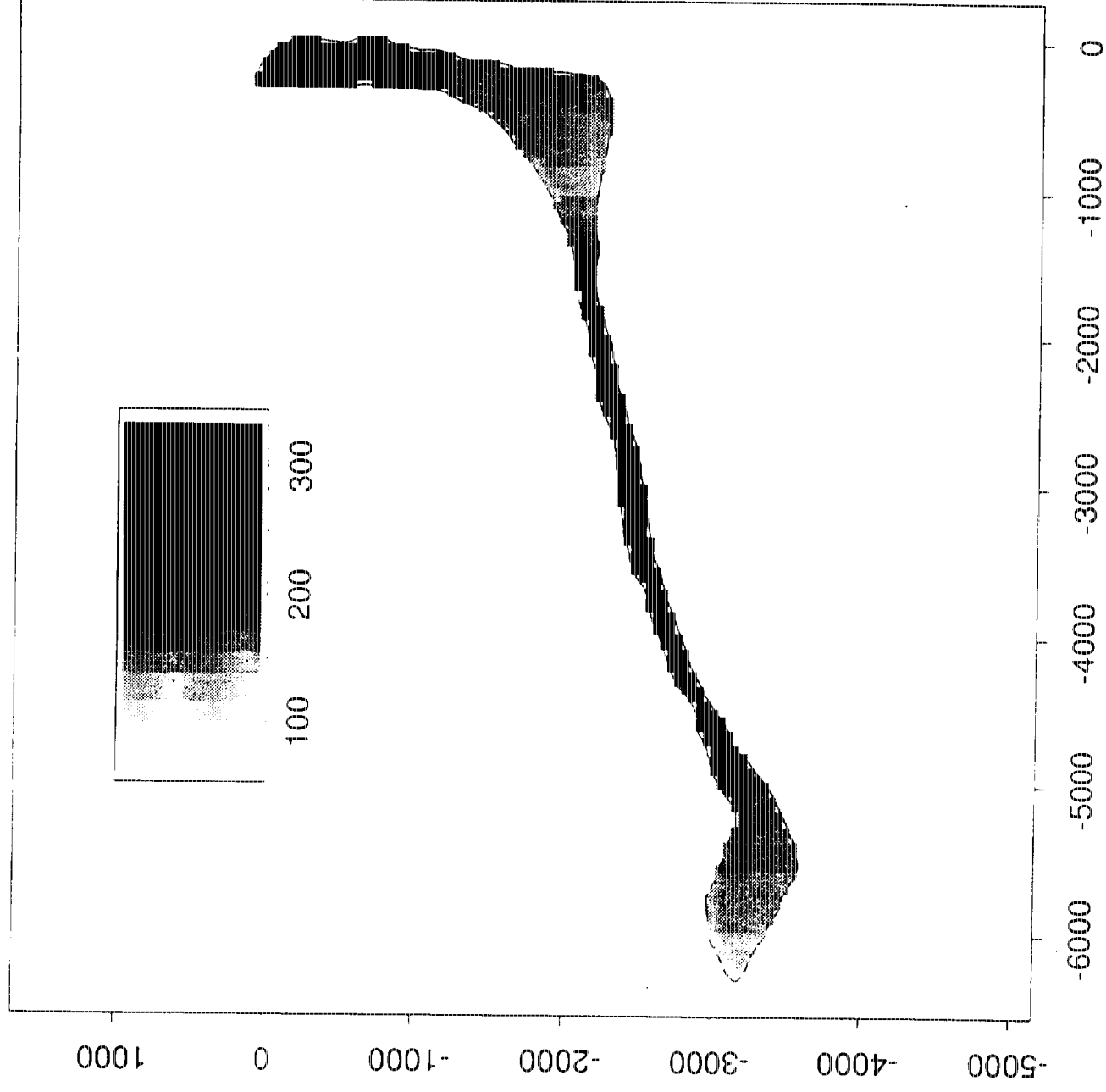


Figure 3j).

Lognormal predictions for Lab Am+Pu (r0=50)

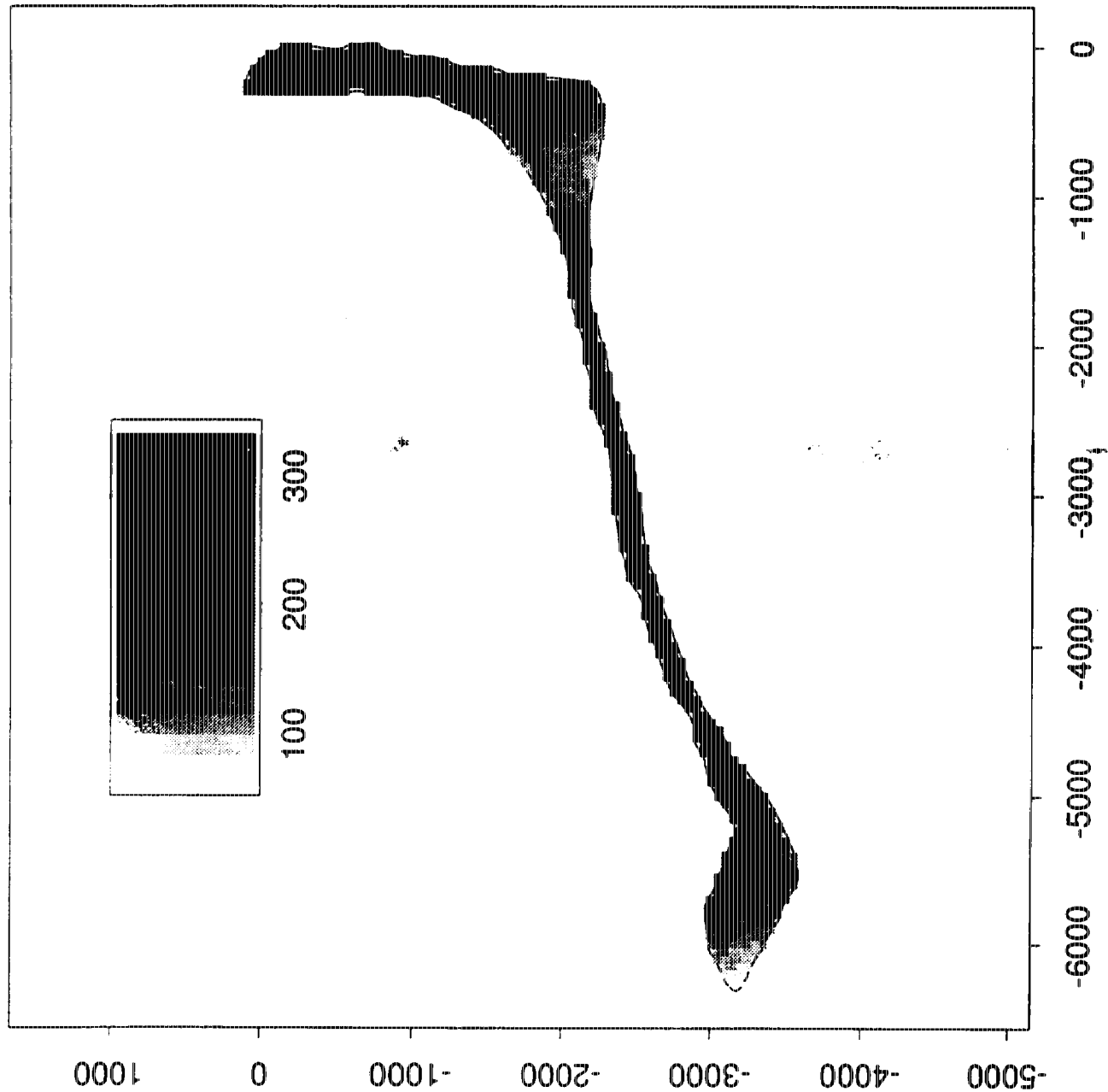


Figure 3g.

Lognormal predictions for Lab Am+Pu ($r_0=100$)

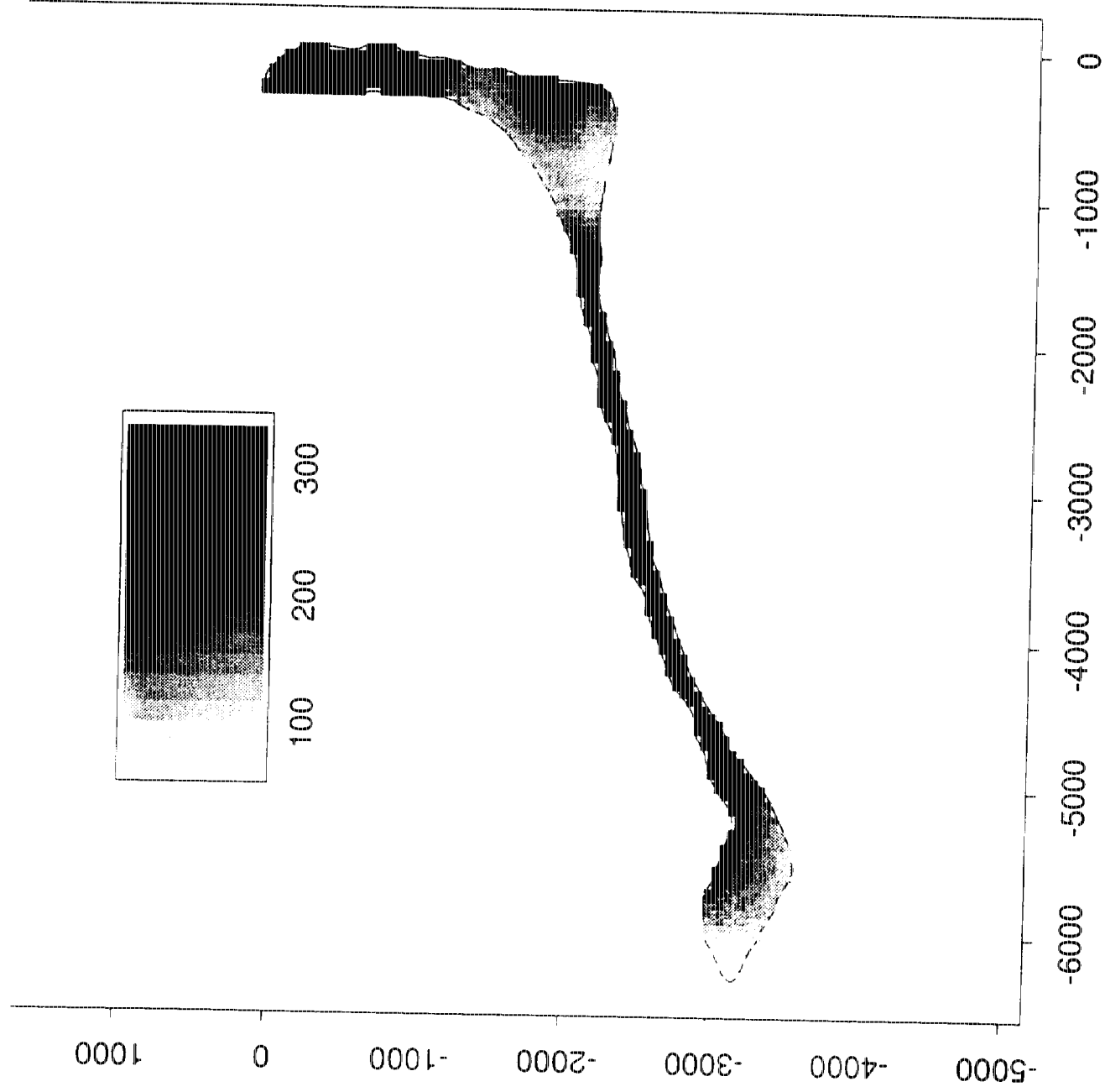


Figure 3h.

Lognormal predictions for Field Cs ($r_0=500$)

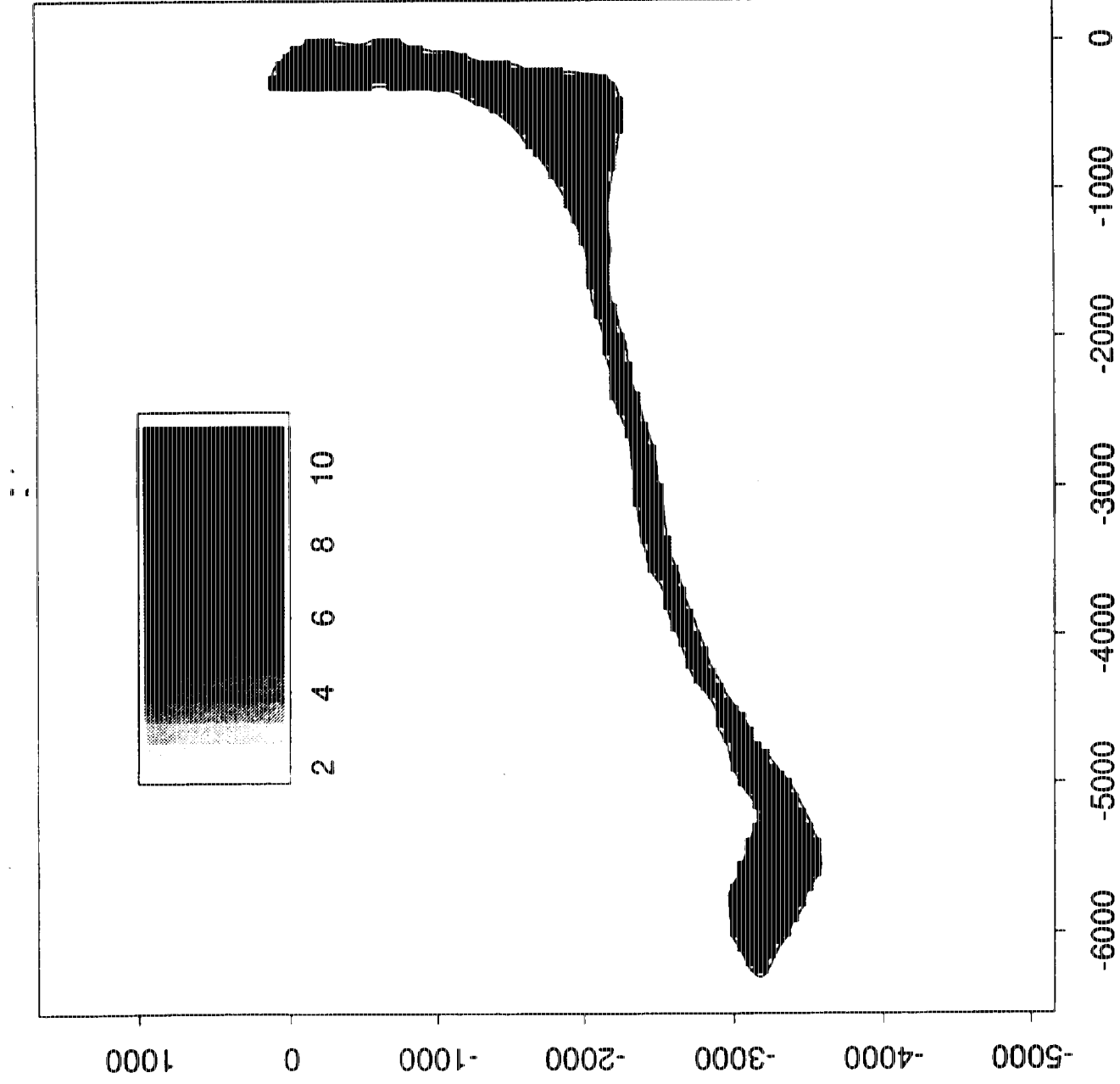


Figure 3e

Lognormal point predictions for Lab Am+Pu

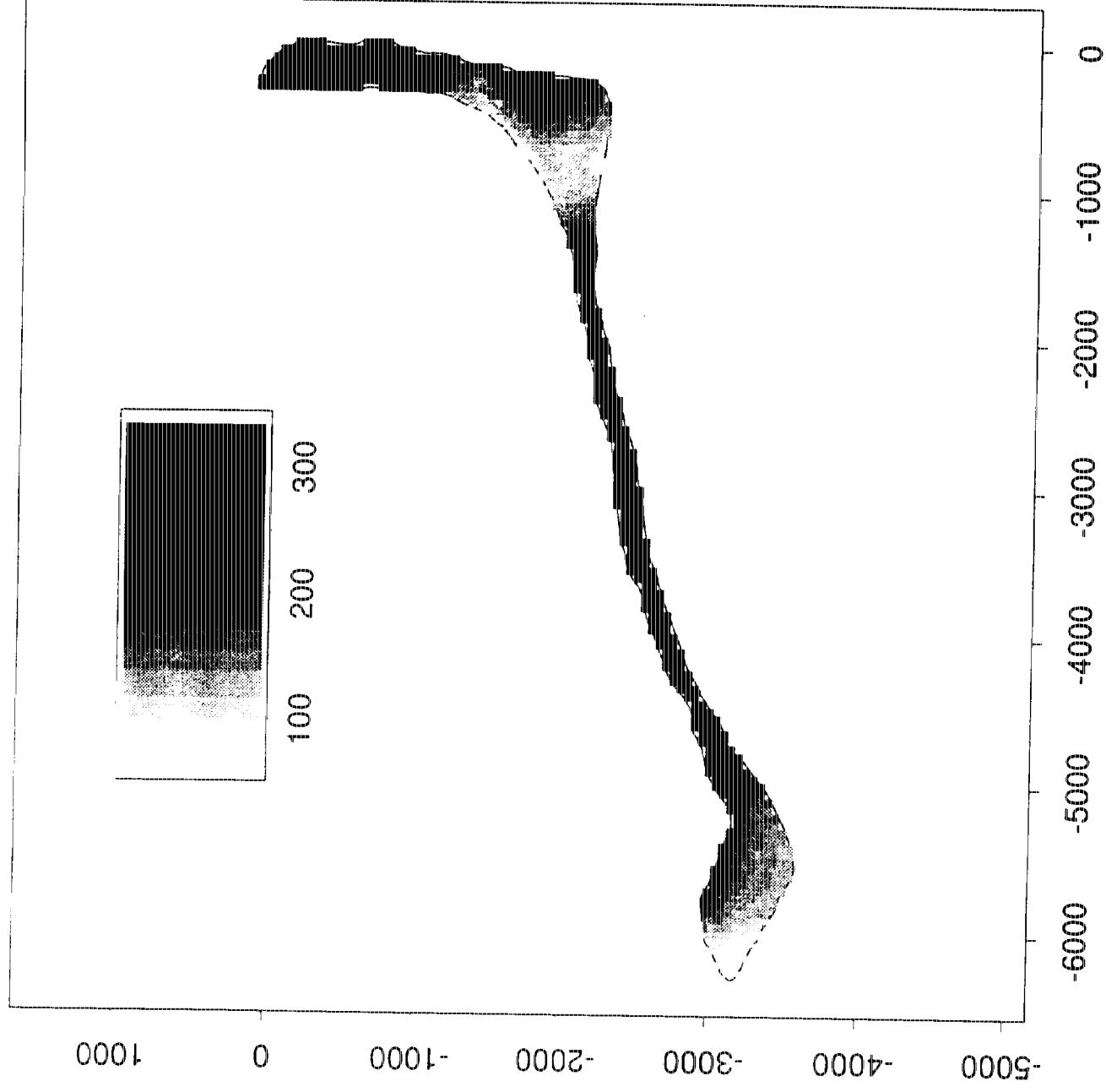


Figure 3f

Lognormal predictions for Field Cs ($r_0=100$)

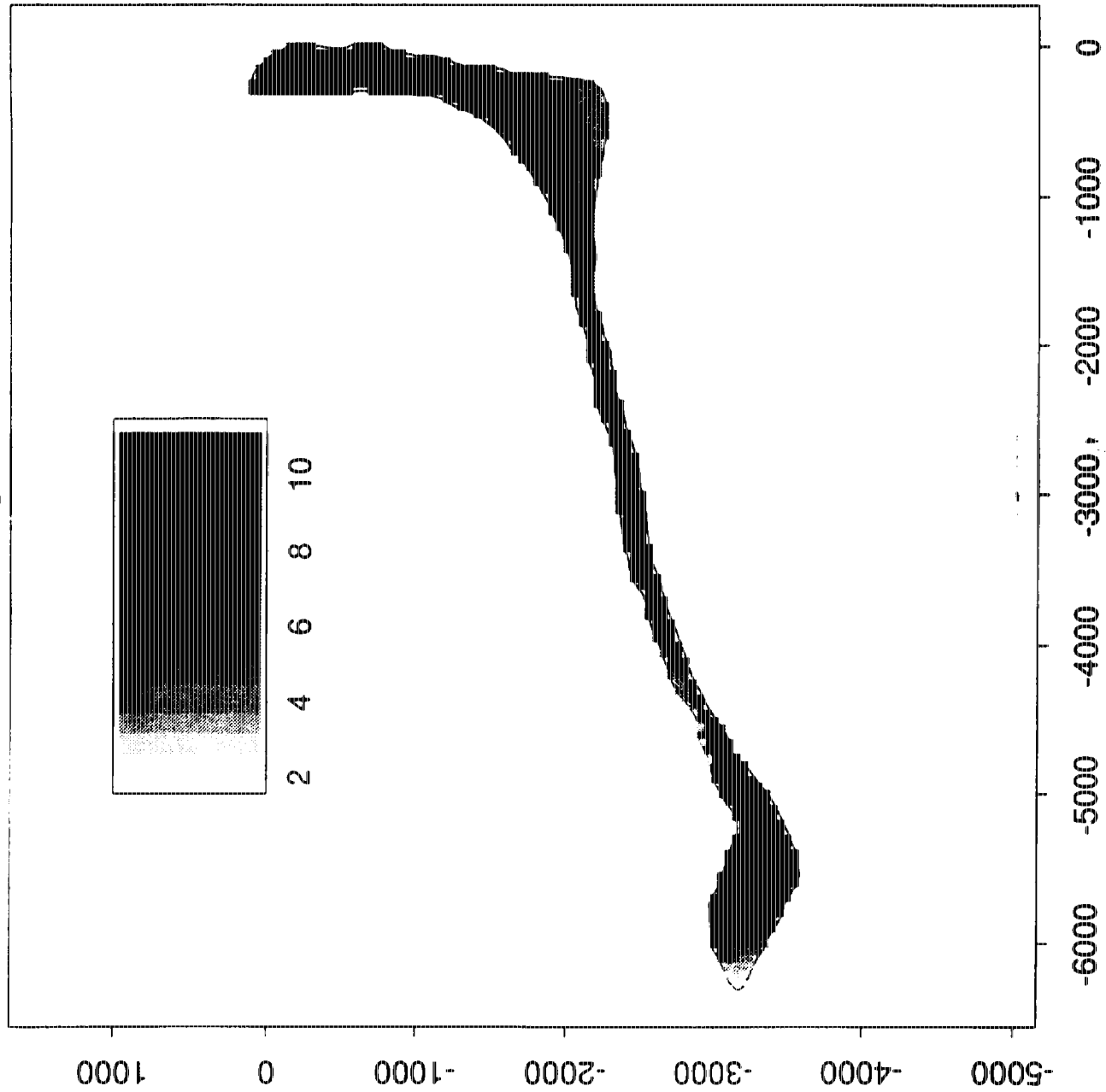


Figure 3c.

Lognormal predictions for Field Cs ($r_0=200$)

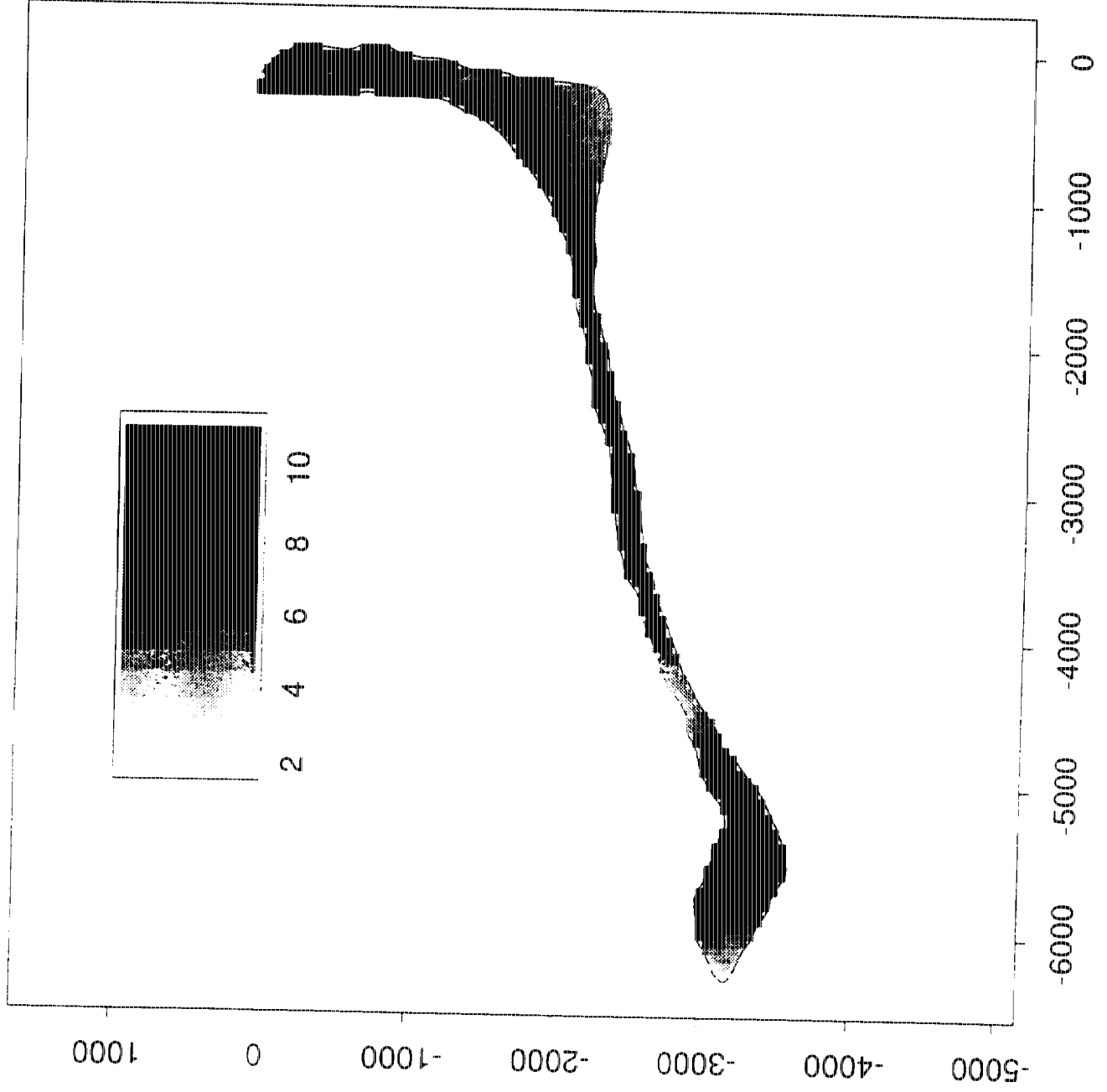


Figure 3d.

Lognormal point predictions for Field Cs

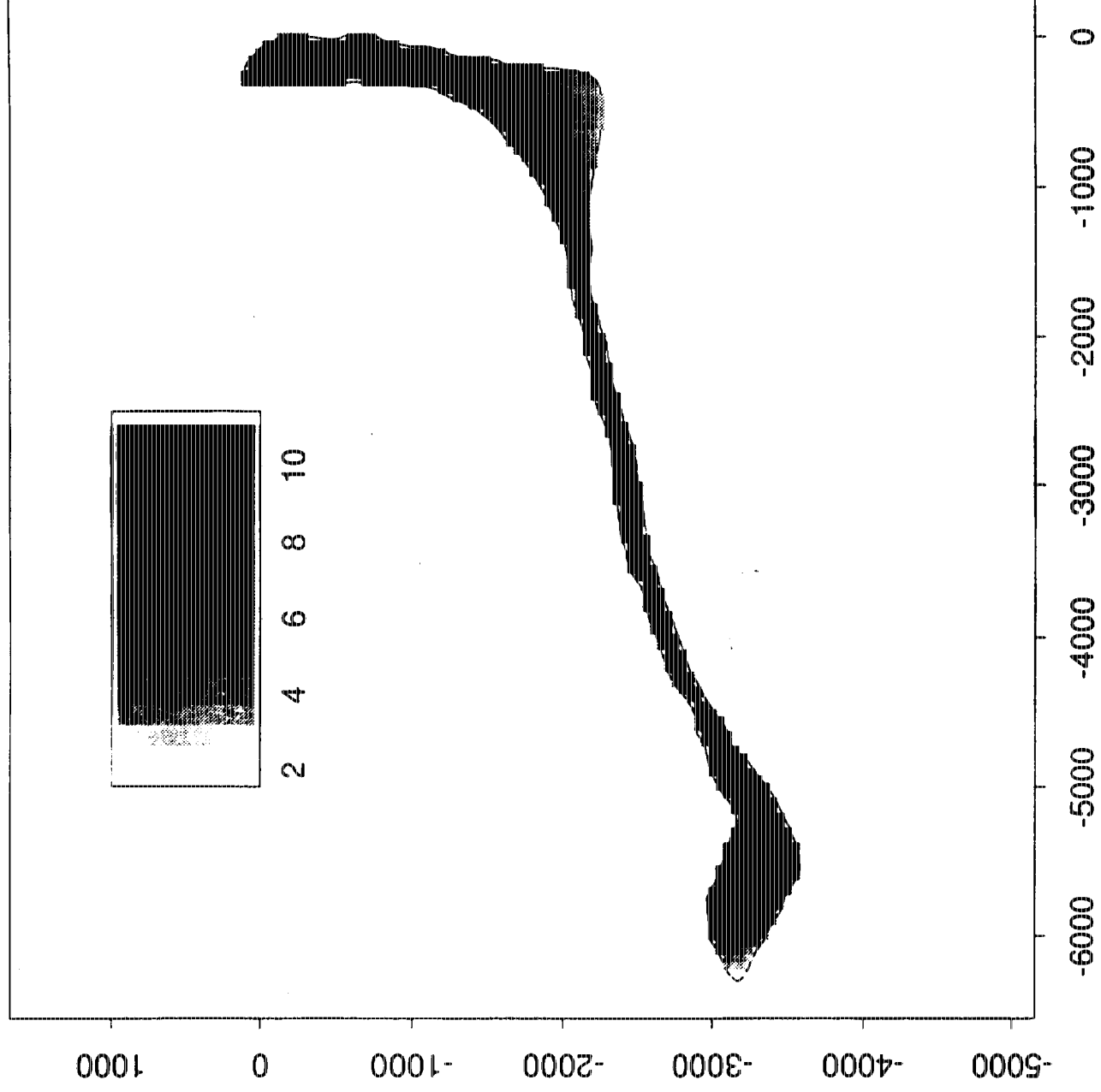


Figure 3a.

Lognormal predictions for Field Cs ($r_0=50$)

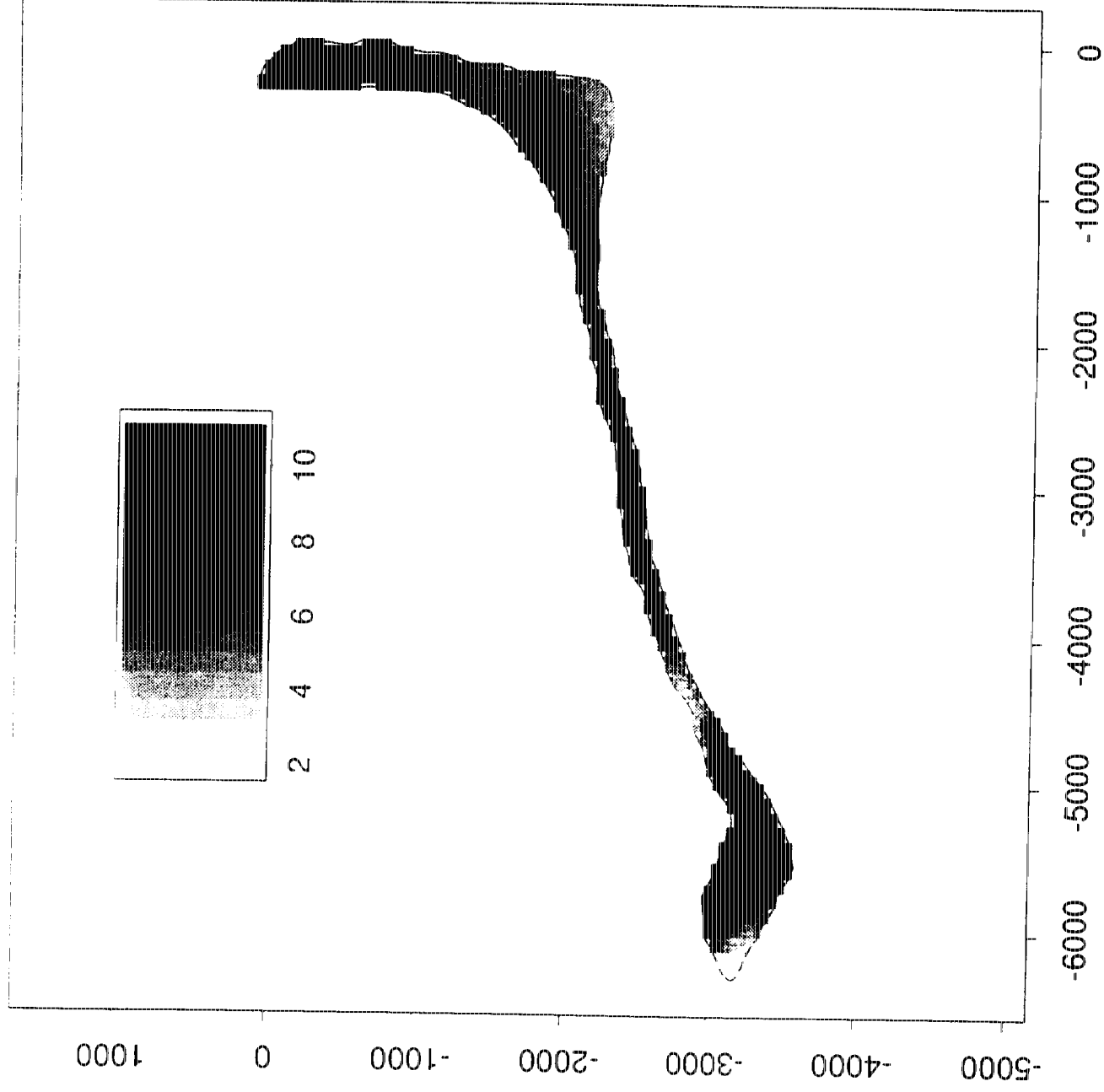


Figure 3b.

Predictions for Lab Am+Pu (r0=200)

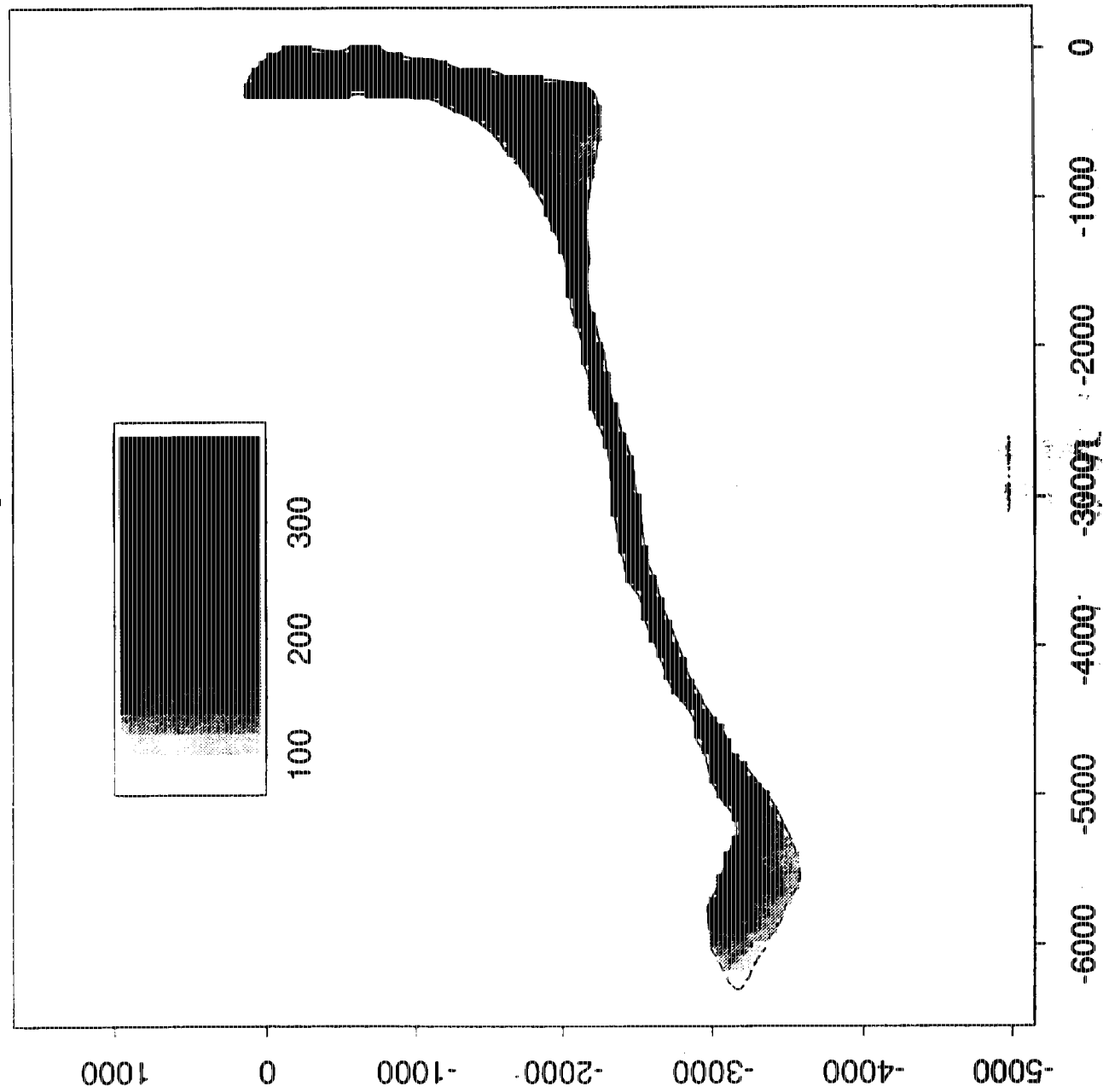


Figure 2i

Predictions for Lab Am+Pu (r0=500)

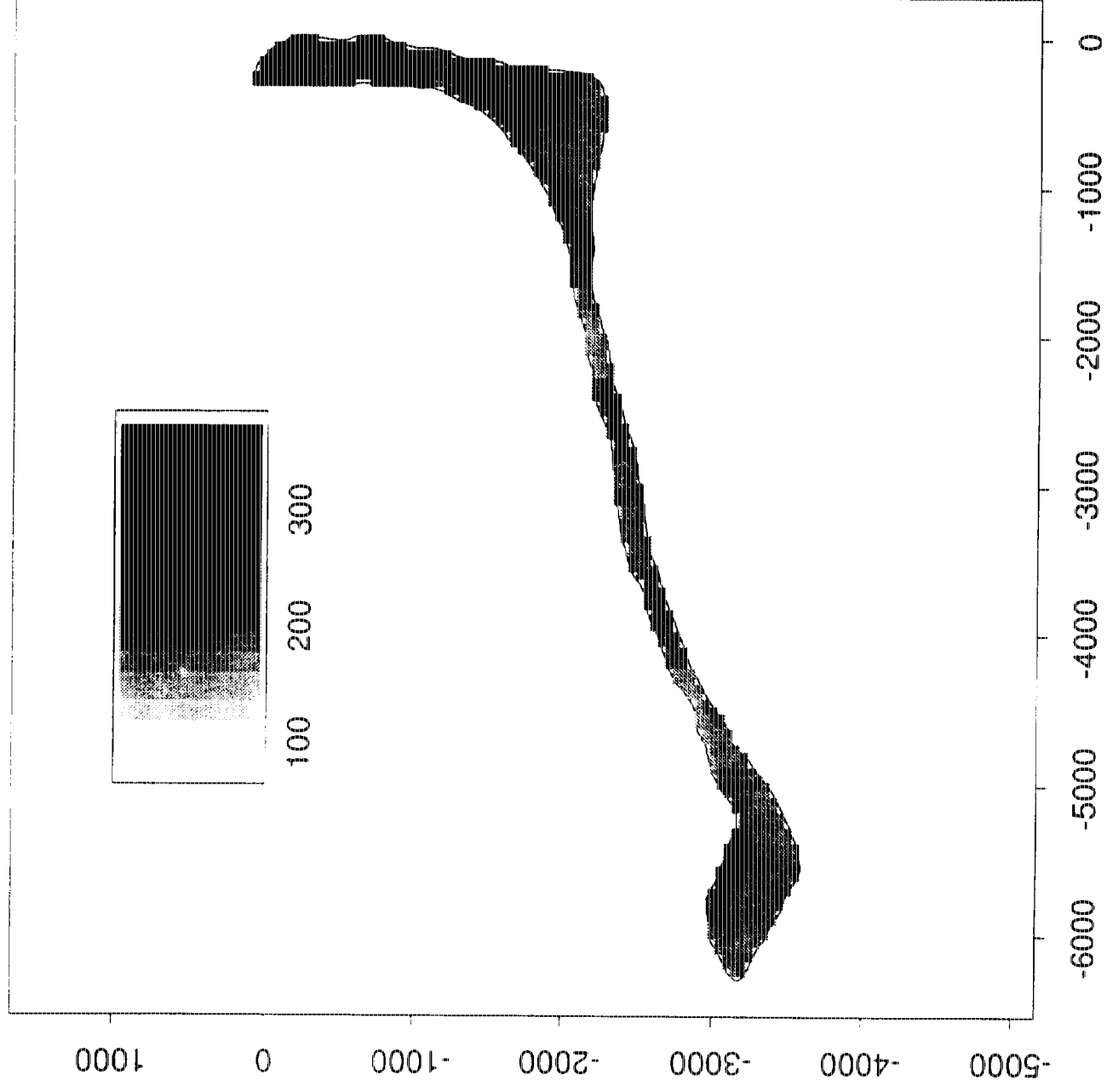


Figure 2j.

Predictions for Lab Am+Pu ($r_0=50$)

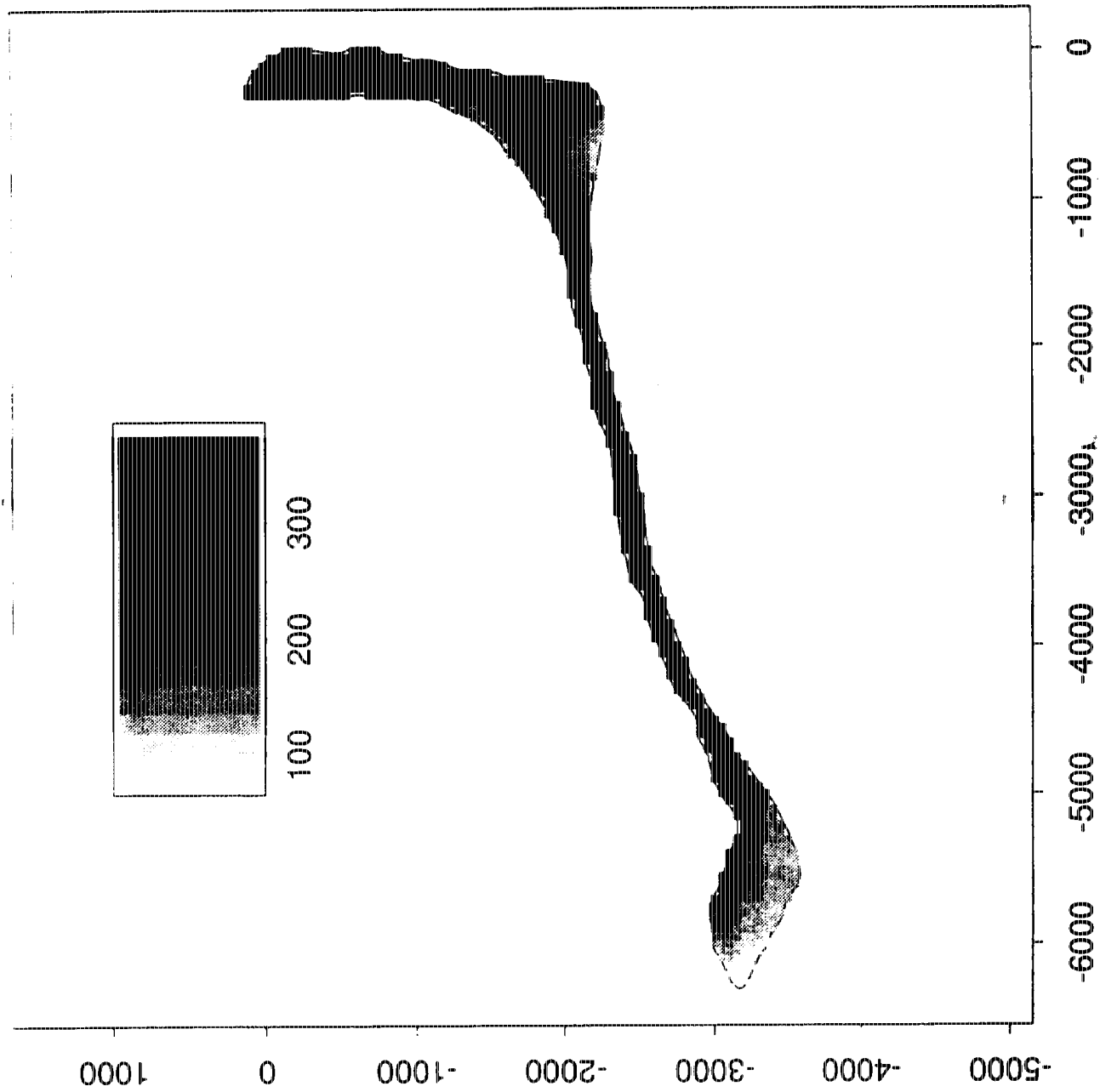


Figure 2g.

Predictions for Lab Am+Pu ($r_0=100$)

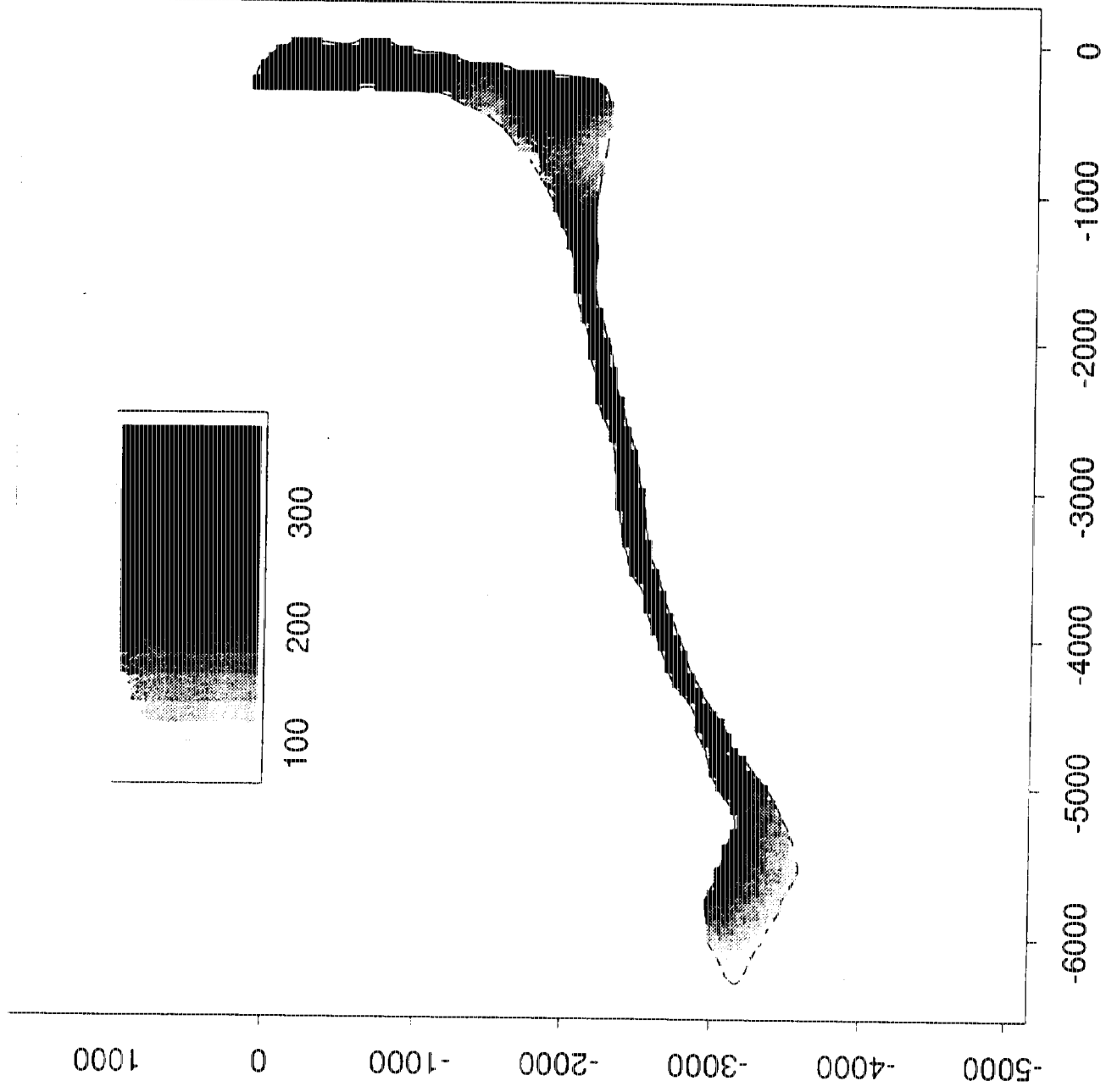


Figure 2h.

Predictions for Field Cs (r0=500)

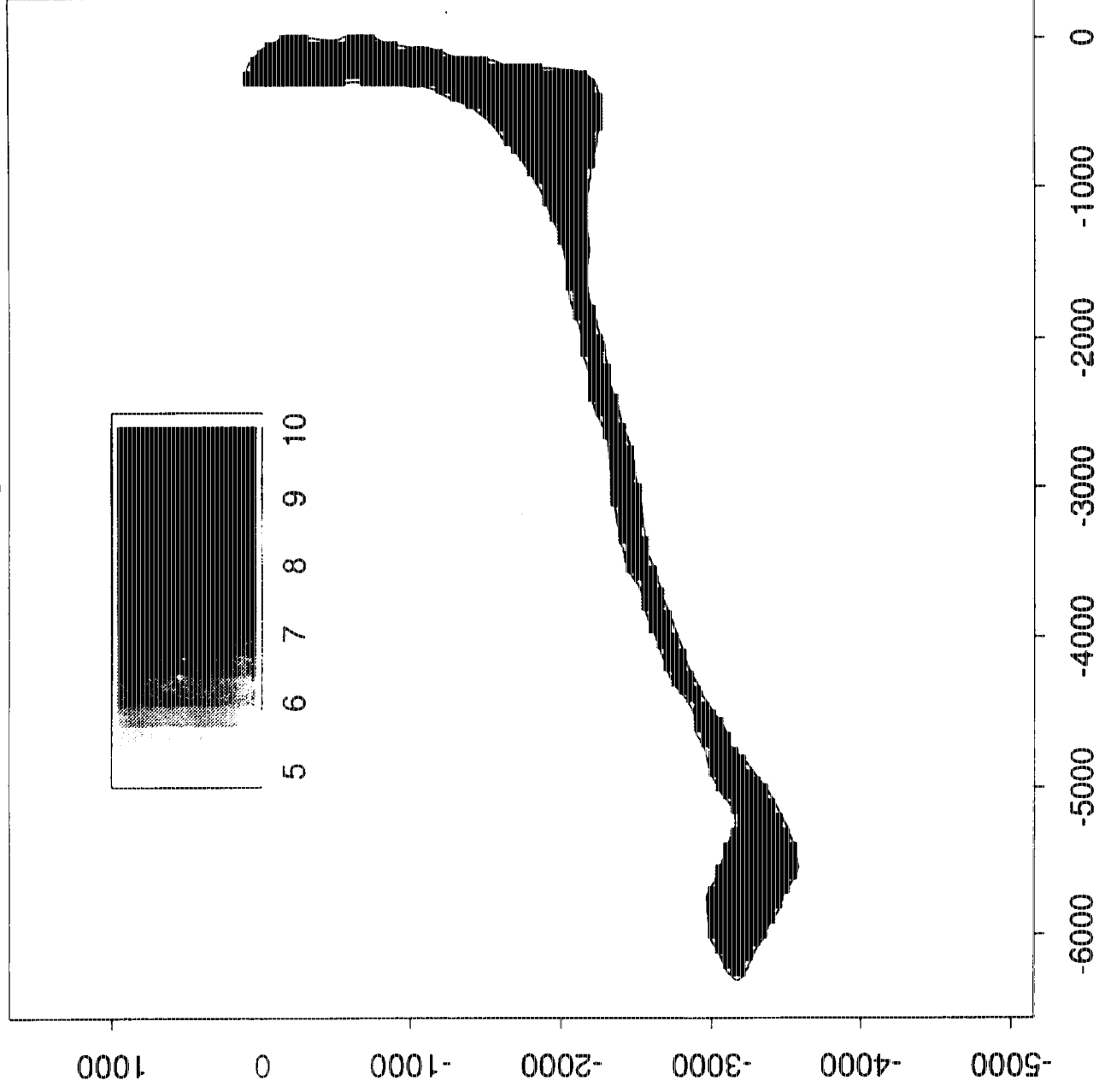


Figure 2e

Point predictions for Lab Am+Pu

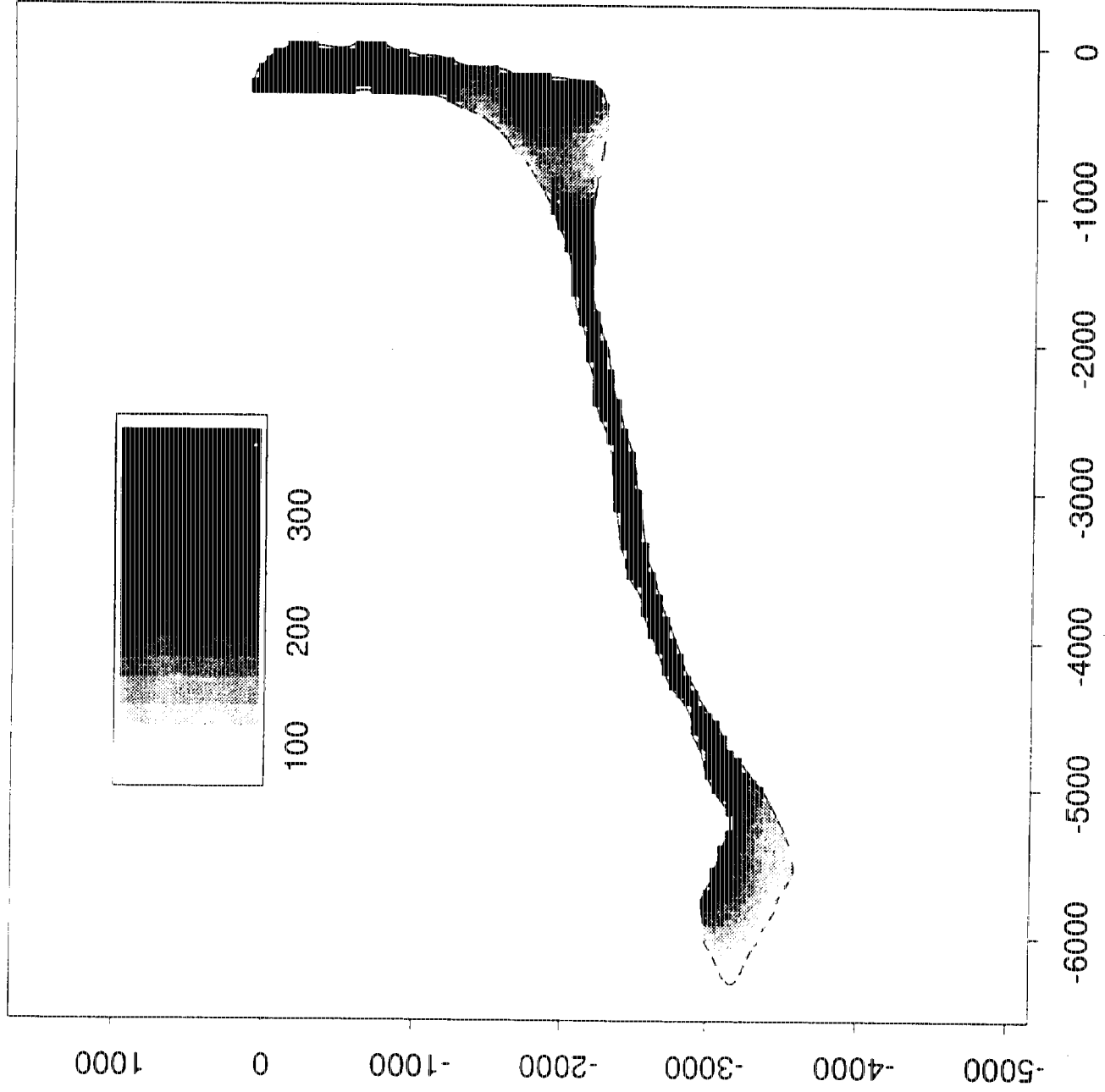


Figure 2f.

Predictions for Field Cs ($r_0=100$)

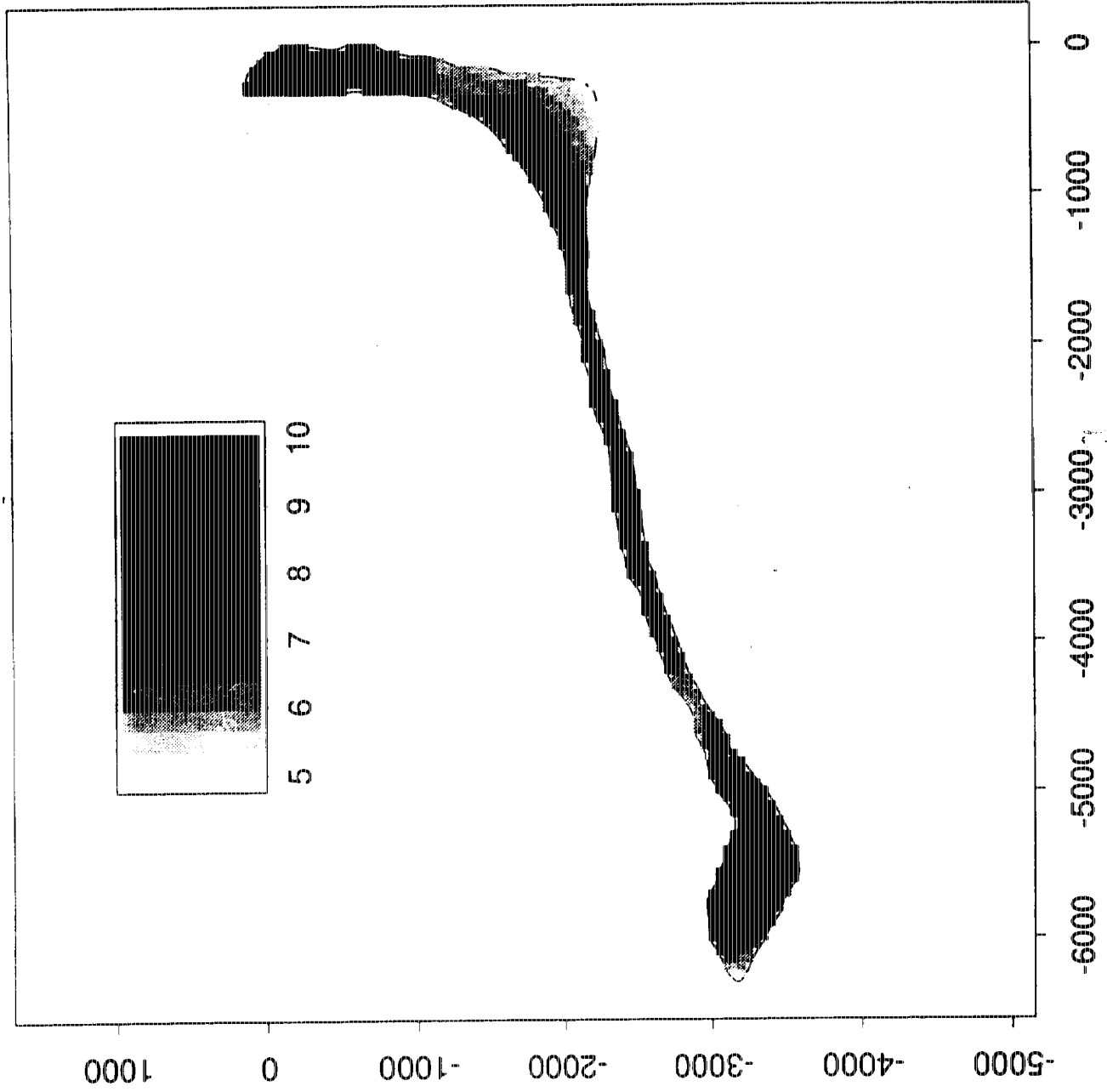


Figure 2c.

Predictions for Field Cs (r0=200)

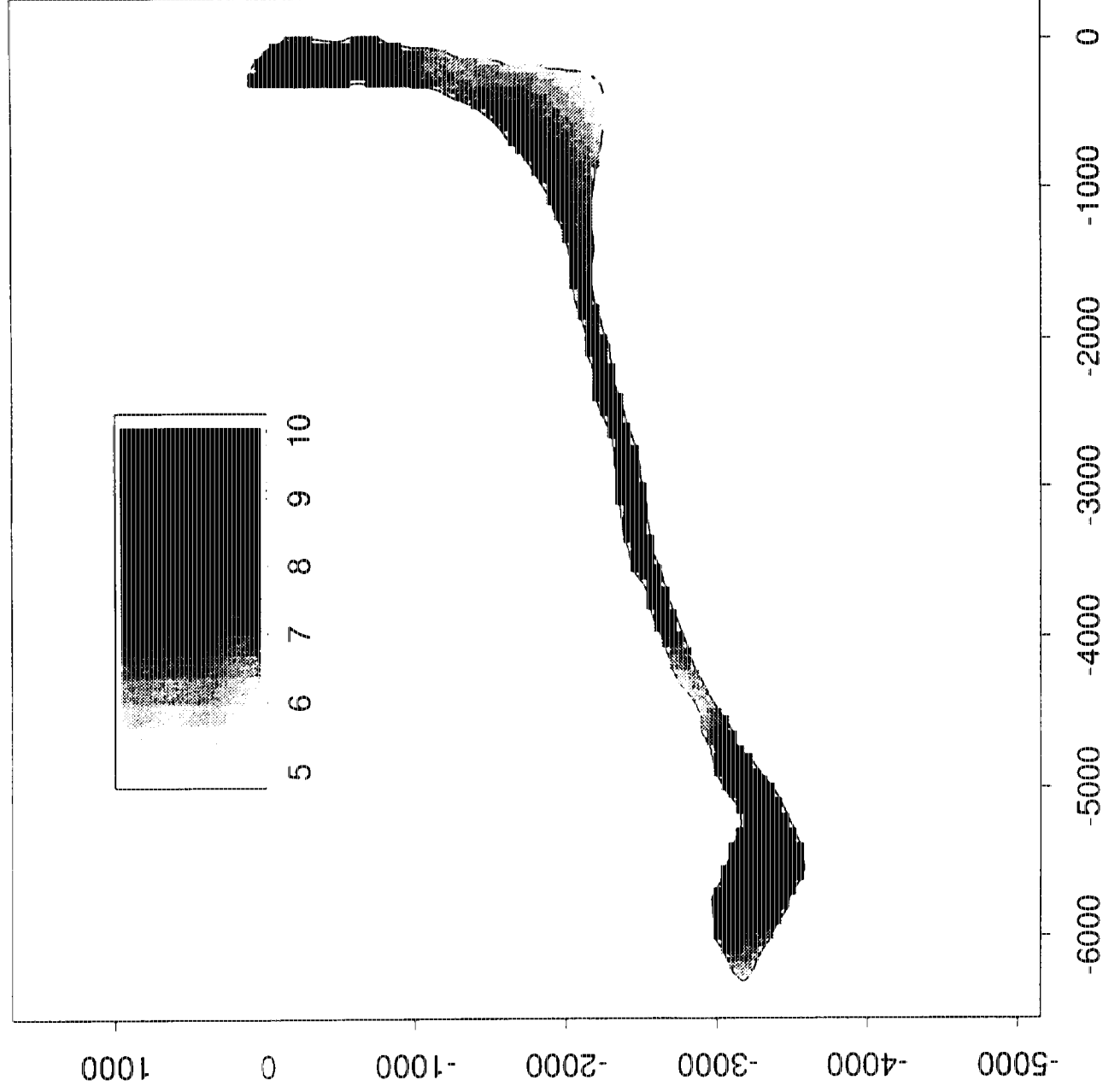


Figure 2d.

Point predictions for Field Cs

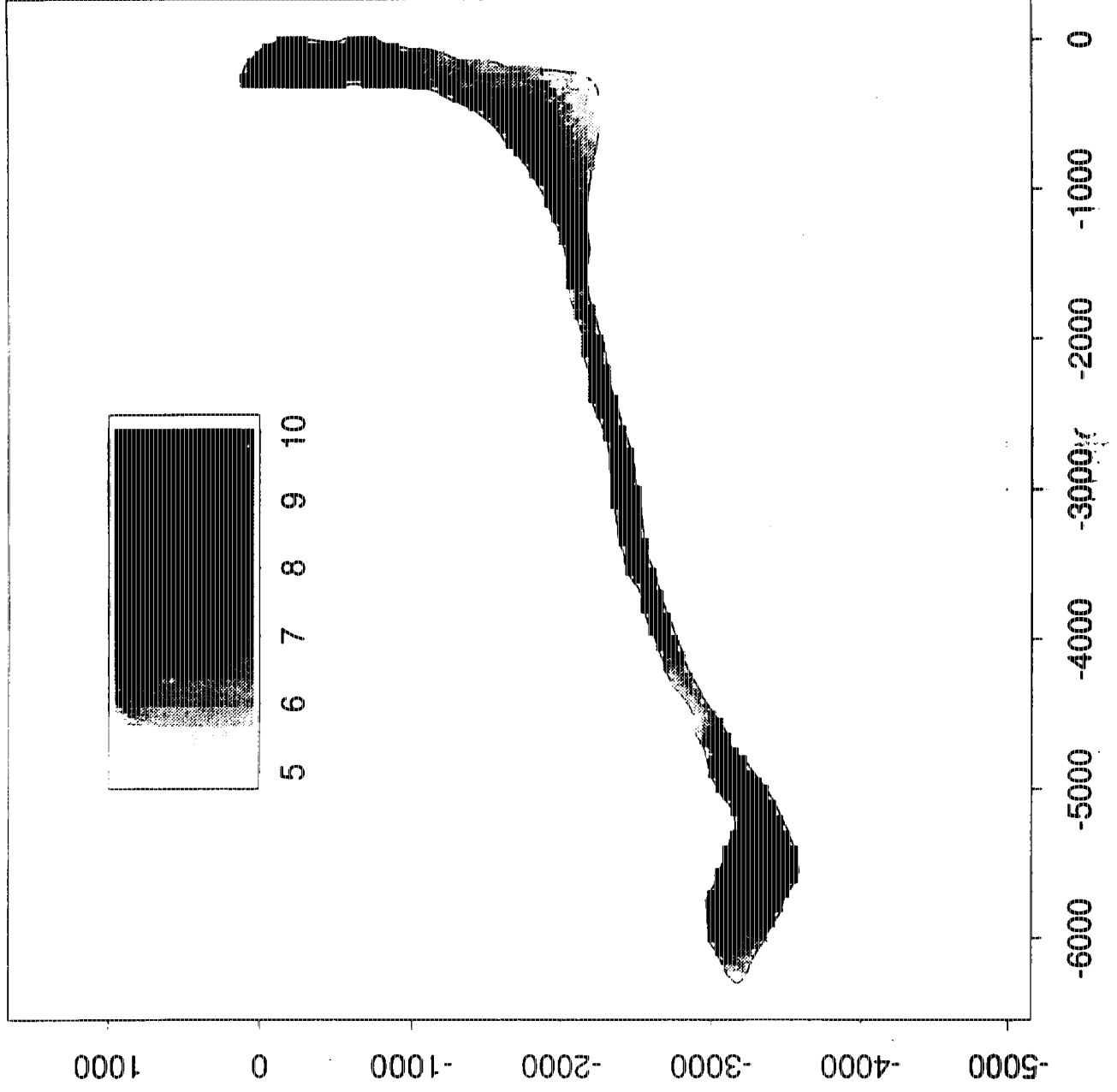


Figure 2a.

Predictions for Field Cs ($r_0=50$)

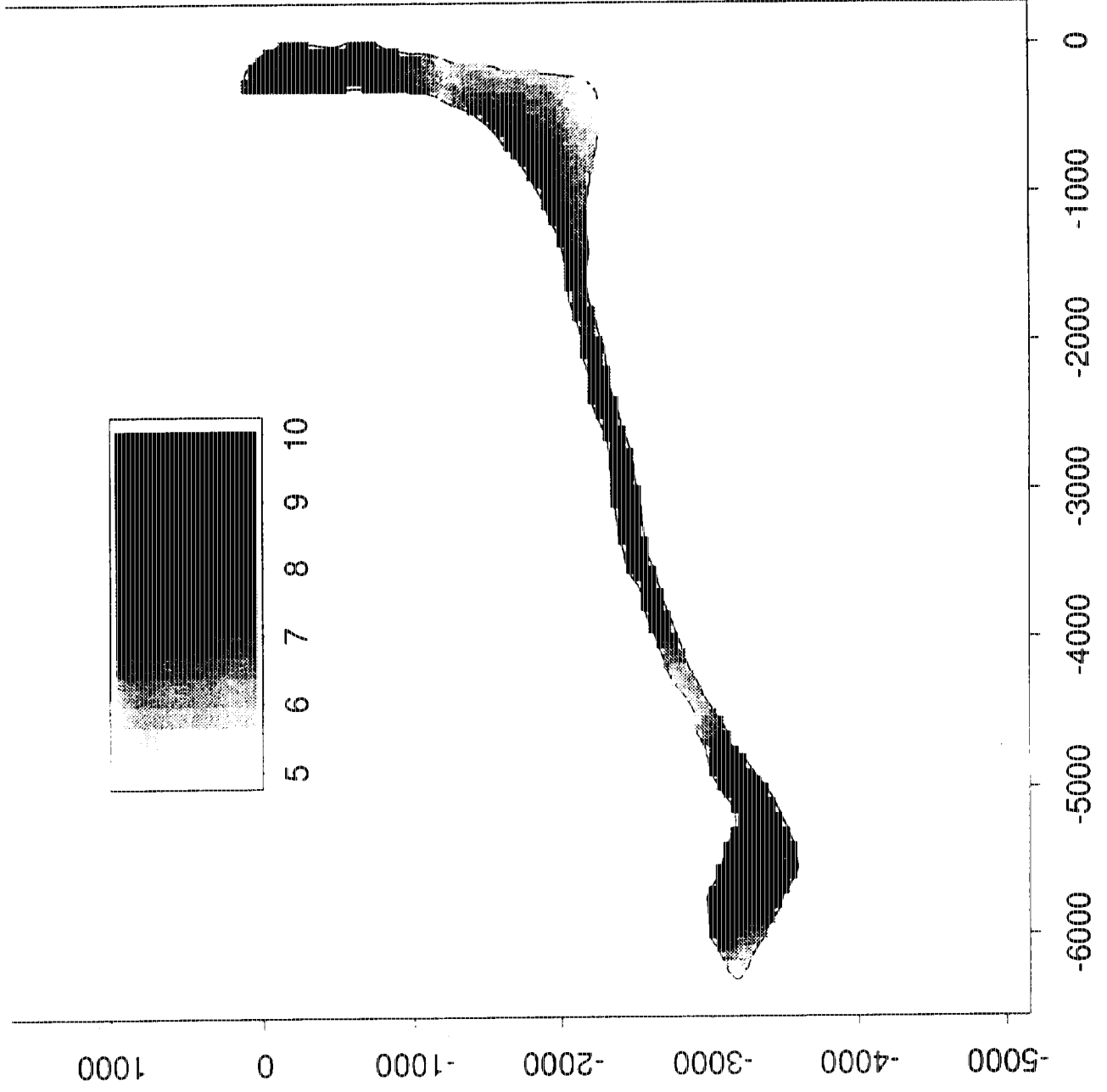


Figure 2b.

log(Field Cs) : sample and fitted variograms

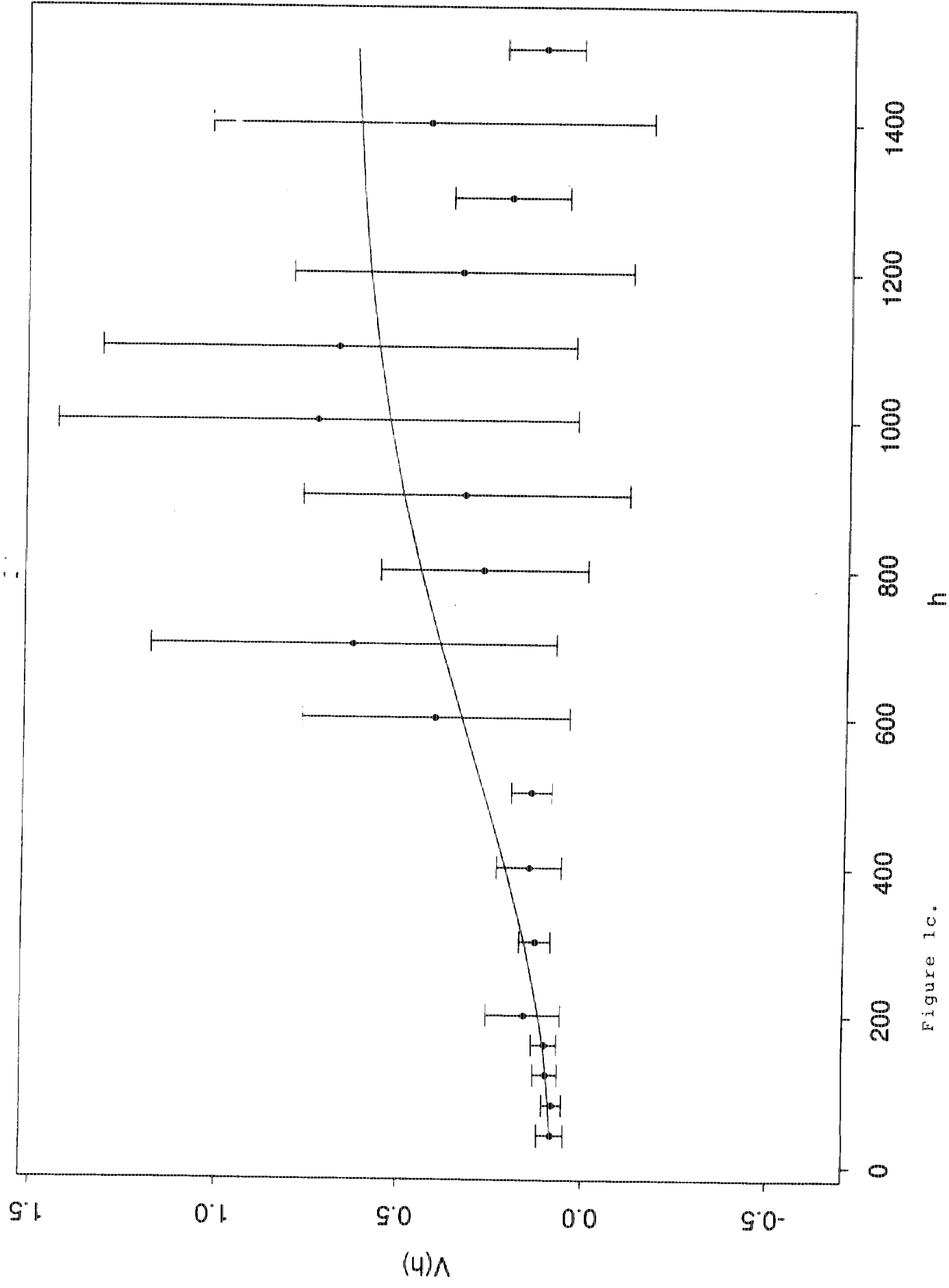


Figure 1c.

Log(Lab Am+Pu) : sample and fitted variograms

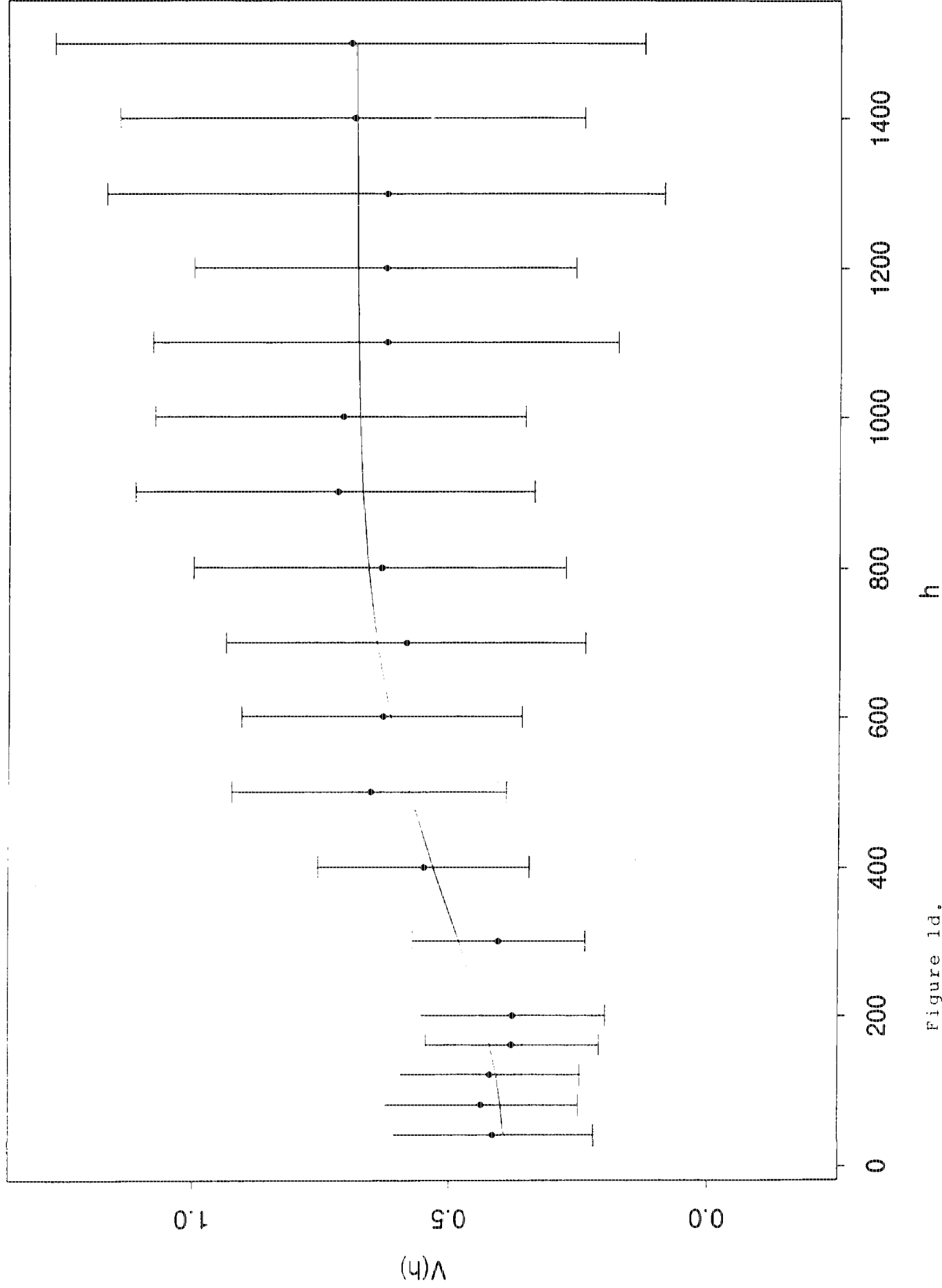


Figure 1d.

Field Cs : sample and fitted variograms

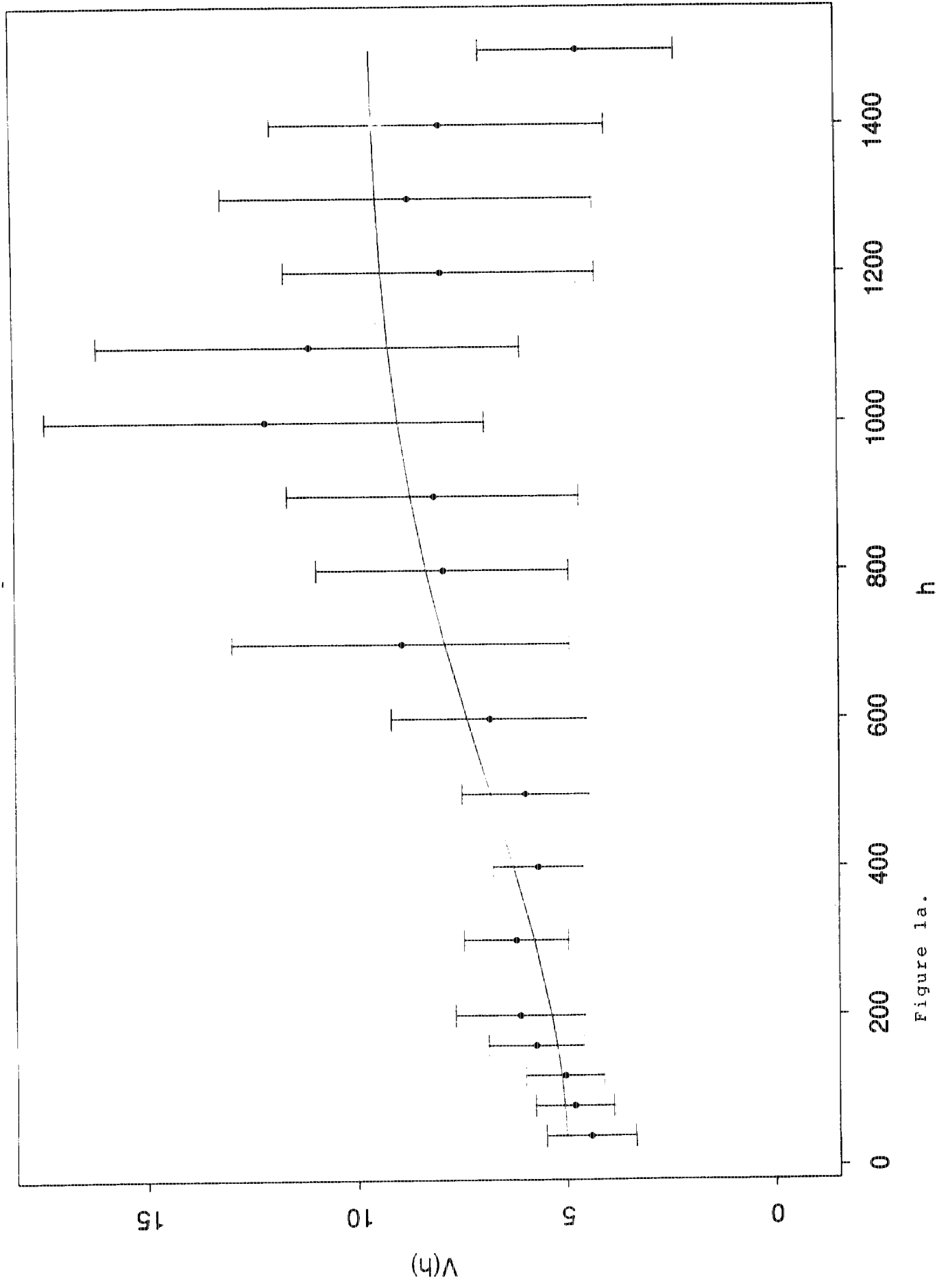


Figure 1a.

Lab Am+Pu : sample and fitted variograms

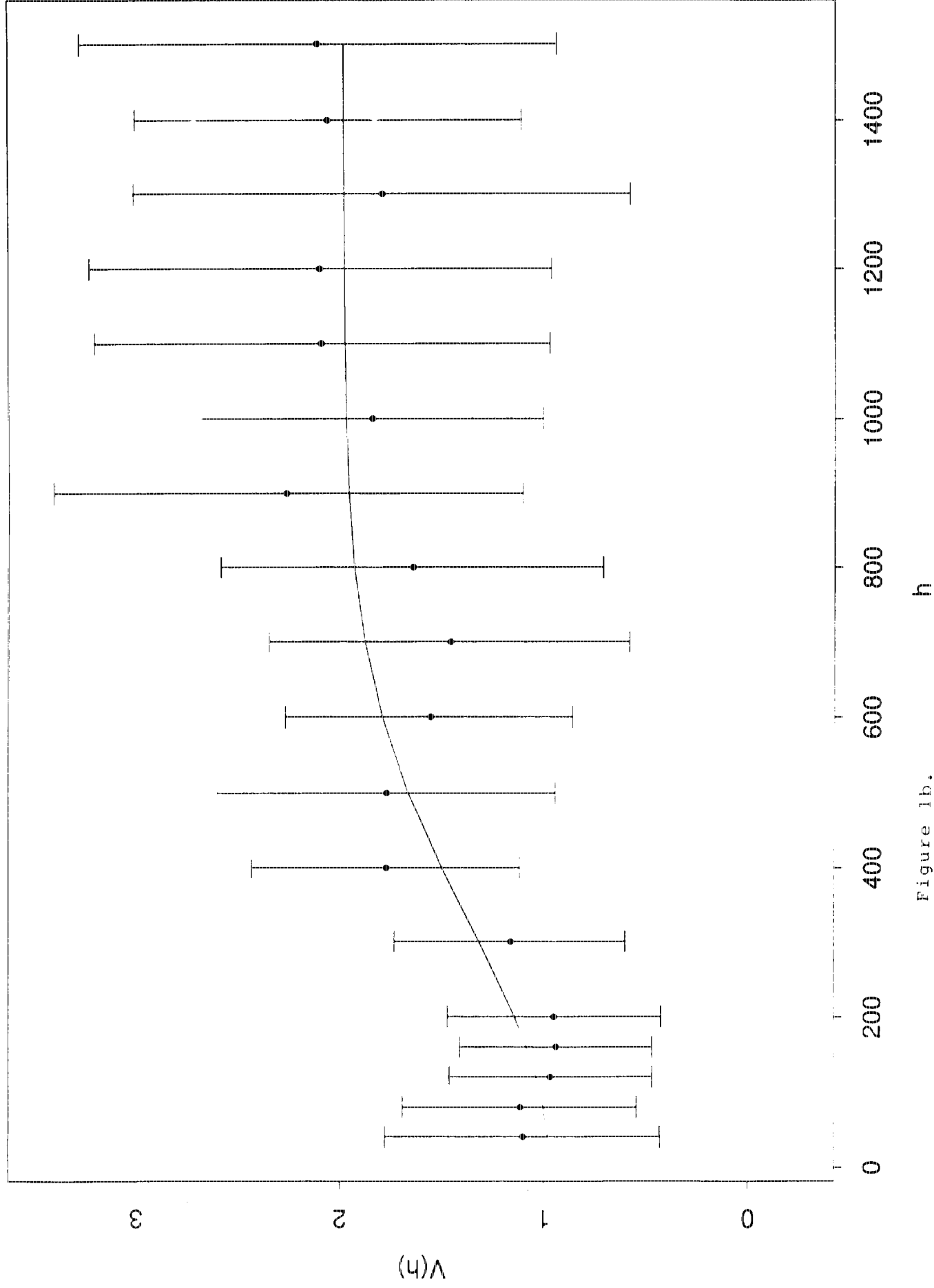
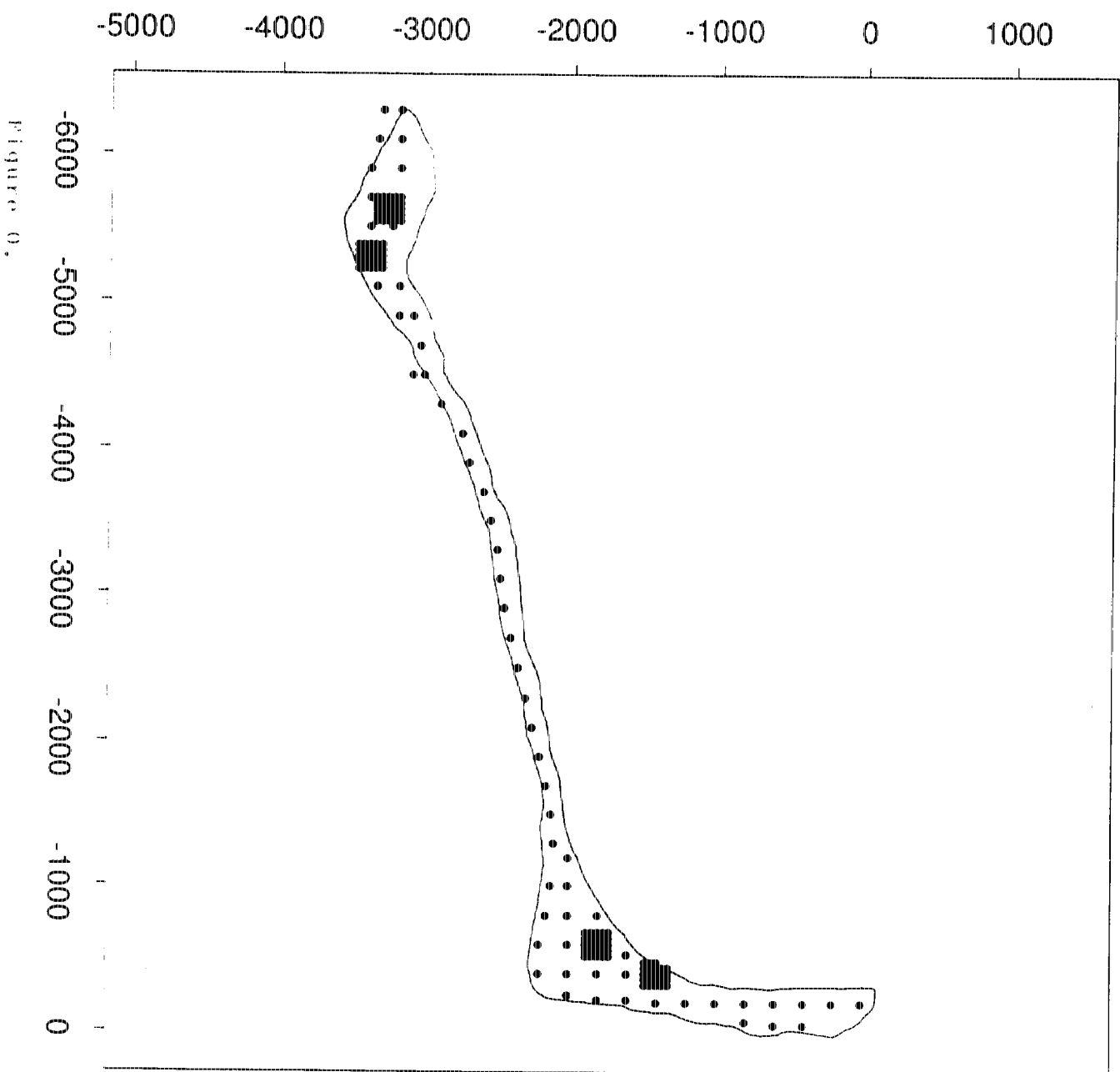


Figure 1b.

Table 1. Parameter estimates for kriging

Response variable	τ^2	σ^2	α
field Cs	4.9982	4.6182	4.5532
lab Am+Pu	0.9731	1.0106	10.5532
log(field Cs)	0.0840	0.5686	3.6750
log(lab Am+Pu)	0.3895	0.2960	9.2900

Locations of observed data



The acid test is how well the model-based predictions actually perform. However, to establish this we need to collect further data, at new locations x , and to compare the predictions $\hat{S}(x)$ with the actual values obtained. In many applications this may be impractical, or at least very expensive. Also, it is important to recognise that whilst poor predictions may be a consequence of using an inappropriate model, they may also simply reflect the inherent difficulty of the prediction problem. In particular, data with a relatively large measurement error component (represented in our models by the parameter τ^2) will be inherently difficult to predict accurately.

Notice that we cannot use the same data for prediction and validation. Were we to attempt this, any interpolator of the data would be judged a perfect predictor, however bizarrely it behaved away from the sample locations.

In the absence of any independent validation data, our judgement of the adequacy of the model is confined to two aspects:

- the goodness-of-fit between sample and fitted variograms.
- a judgement on whether the model assumptions and fitted parameter values are physically sensible.

With respect to the first of these, the comparisons between sample and fitted variograms in Figure 1 suggest a reasonably good fit for either the ordinary or log-Normal kriging models. Our preference for the log-Normal model is based on its physical interpretation. Specifically,

1. the noise-to-signal ratio $\hat{\tau}^2/\hat{\sigma}^2$ is much smaller for the log-Normal than for the ordinary kriging model, and more in line with the experimenter's intuitive judgement of what is appropriate for these data.
2. the multiplicative model which underlies log-Normal kriging is a closer approximation to the actual measurement process than is the additive model of ordinary kriging.

4 Future developments

We believe that the maps based on log-normal kriging are the best estimates of the spatial variation in radionuclide concentrations which we can provide using current geostatistical methodology. In particular, we prefer these to the maps based on kriging the untransformed data because the experimental background suggests strongly that the variance of the measurement error should be related to the underlying true concentration.

We see two potentially fruitful areas for further research, which we propose to develop over the next two years.

Firstly, the physical data-collection process is such that a very plausible probability model for the untransformed data, Z_1, \dots, Z_n , would be that the Z_i are conditionally independent Poisson-distributed random variables with means $S(x_i)$, given an underlying spatial process $S(x)$. In this model, $S(x)$ again represents the true underlying concentration, and could be modelled as a correlated Gaussian process. We propose to develop analogues of the kriging

methodology which explicitly incorporate a Poisson probability model for the data conditional on $S(x)$. In principle, this physically based model should yield a further improvement over the qualitatively sensible, but *ad hoc* assumptions which underly log-normal kriging.

Secondly, the optimality property of the predictor $\hat{S}(x)$ is preserved for predicting linear functionals of $S(x)$, an example of which is the simple form of the areal average predictor, $\hat{T}(x)$. However, it is not preserved for more general quantities which may be of interest, for example maximal concentrations over the island. Thus, whilst it is reasonable to take the location and value of the maximum of the $\hat{S}(x)$ map as an estimate of the location and value of the maximum of $S(x)$, it should be possible to derive better estimates by developing a more general theory of spatial prediction. Also, simply reading off the location and value of the maximum from the $\hat{S}(x)$ map gives no indication whatsoever of the precision of this estimate. Again, a more general theory should address this question.

References

- Cressie, N. (1985). Fitting variogram models by weighted least squares. *Journal of the International Association for Mathematical Geology*, **17**, 563-86.
- Whittaker, J.C. (1990). *Graphical Models in Applied Multivariate Statistics*. Chichester : Wiley.

3 Kriging

3.1 Method

Kriging is a minimum mean-square-error method of spatial prediction. Specifically, to predict the value of $S(x)$ at any location x , the predictor $\hat{S}(x)$ is chosen to minimise the mean-squared prediction error

$$MSPE(x) = E\{\{S(x) - \hat{S}(x)\}^2\}$$

The general solution to this problem is

$$\hat{S}(x) = E[S(x)|Z],$$

the mean of the conditional distribution of $\hat{S}(x)$ given the data $Z = (Z_1, \dots, Z_n)$.

Under the assumption that $S(\cdot)$ and $Z(\cdot)$ are stationary Gaussian processes, each with mean μ , standard results on the multivariate Normal distribution (e.g. Whittaker, 1990, chapter 5) can be used to show that

$$\hat{S}(x) = \mu + V_{sz}(V_{zz})^{-1}(z - \mu) \quad (7)$$

where V_{zz} is the variance matrix of the random vector Z , and V_{sz} is the vector of covariances between $S(x)$ and the elements of Z .

From the assumed properties of $Z(\cdot)$ and $S(\cdot)$, it can be shown that the explicit form of the above result is

$$\hat{S}(x) = \mu + c'(\sigma^2 R + \tau^2 I_n)^{-1}(z - \mu) \quad (8)$$

where $c' = \sigma^2\{\rho(\|x - x_1\|), \dots, \rho(\|x - x_n\|)\}$, R is the correlation matrix of Z , i.e the $(i, j)^{th}$ element of R is $\rho(\|x_i - x_j\|)$, and I_n is the $n \times n$ identity matrix.

The theory leading to formula (7) for the predictor $\hat{S}(x)$ can equally well be used to derive the minimum mean-square-error predictor for areal averages $T(x)$, as defined by (5). The result is the intuitively sensible predictor,

$$\hat{T}(x) = (\pi r_0^2)^{-1} \int \hat{S}(x - y) dy. \quad (9)$$

3.2 Results

The assumed correlation model and estimated values of the model parameters, θ , can now be used in (8) to predict values of each variable over the island. The results of the kriging analyses applied to the untransformed concentrations are displayed graphically in Figure 2.

The main points to notice from Figure 2 are:

1. Estimates of Cs appear to be generally higher in the south-west of the island and in the middle of the narrow central area, and lower in the north-east.
2. Estimates of Am+Pu are also high in the middle of the narrow central area. However, in contrast to the results for Cs, estimates are high in the north-east, and generally lower in the south-west.

3. As expected, the maps of $\hat{T}(x)$ become spatially smoother and less variable as the averaging radius, τ_0 , increases

3.3 Log-normal kriging

When the kriging methodology outlined in section 3.1 is applied to log-transformed data, the resulting predictor $\hat{S}(x)$ is optimal, in a mean-square-error sense, for the log-concentration at the point x . Because the log-transformation is non-linear, it does not follow that $\exp\{\hat{S}(x)\}$ is the optimal predictor for the concentration – we need to apply a bias correction. The resulting minimum mean-square-error predictor is given in Cressie (1990, p135), and can be derived as follows.

We assume that the log-transformed data, $Z_i = \log Y_i$ say, follow the basic model (1), in which we further assume that $S(x)$ is a Gaussian process. Our objective is to predict $T(x) = \exp\{S(x)\}$ at an arbitrary point x . By the general theory of minimum mean square error prediction, the optimum predictor is

$$\hat{T}(x) = E[T(x)|Z].$$

Now, conditional on Z , the random variable $S(x) = \log T(x)$ has a Normal distribution with mean μ_x and variance σ_x^2 , say. Thus, under the same conditioning, $T(x)$ has a log-Normal distribution with mean

$$E[T(x)|Z] = \exp(\mu_x + \frac{1}{2}\sigma_x^2) \quad (10)$$

and variance

$$\text{Var}(T(x)|Z) = \{E[T(x)|Z]\}^2 \{\exp(\sigma_x^2) - 1\} \quad (11)$$

It follows that the minimum mean square error predictor, $\hat{T}(x)$, is given by (10), with prediction variance given by (11), in which $\mu_x = E[S(x)|Z]$ and $\sigma_x^2 = \text{Var}(S(x)|Z)$ are obtained in the standard manner.

3.4 Results

The assumed correlation model and estimated values of the model parameters can again be used to predict values of each variable over the island. The results of the log-normal kriging analyses are displayed graphically in Figure 3.

The main features of these maps are qualitatively similar to the corresponding maps in Figure 2. The most important quantitative difference is that the log-normal estimates are more faithful to the data, in the sense that the range of the point estimates over the island is closer to that of the data – this is especially true of the C's map.

3.5 Validation

The theory of kriging provides mean-square-optimal predictions *under the assumed stochastic model for the data*. The models underlying ordinary and log-Normal kriging are different. This raises the question of how we can be reasonably sure that our model is appropriate.



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Rongelap Resettlement Project

Study of Traditional or "Local Food Only" Diet

Executive Summary¹

November 1994

Bernd Franke, Scientific Management Team

¹ a copy of the complete report with appendices can be obtained from IEER



1 Objective

It is the objective of the study to define a reasonable diet consisting of entirely local foods for use in the assessment of radiation doses in the event of resettlement on the Southern part of Rongelap Atoll. The Memorandum of Understanding defines the problem as follows:

"The "local food only diet" declaration is meant to constitute a traditional Rongelapese diet consisting of local food taken, grown and/or gathered from the southern islands of Rongelap Atoll and the immediately surrounding waters (...). It is agreed that the makeup of a Rongelap "local food only diet", and for comparison purposes a more "realistic diet", shall be more precisely determined and quantified pursuant to the Rongelap Work Plan, in consultation with the Rongelap community."

The diet study therefore has to answer two distinct questions:

1. Which dietary intake can "the maximally exposed individual" be reasonably assumed to have ?
2. How can a "more realistic diet" be defined which reflects the situation of Rongelap residents after resettlement ?

2 Methodological considerations

For more than 100 years, the Marshallese diet has consisted of a mixture of imported and local foods. From the period of the Germans in the mid-1800s, the Japanese, and finally the Americans, the Marshallese people have subsisted on varying types and quantities of imported food as an adjunct to their abundant but monotonous marine-based diet. As atoll dwellers [and not agriculturists] the Marshallese and other people living in Pacific atolls have the most restricted diet of all oceanic peoples.

A local food only diet cannot be measured directly since there appears to be no population in the Marshall Islands which subsides for longer periods of time on a diet consisting of entirely local food items with no consumption of imported foods. Even if one were to conduct a dietary survey on more traditional islands, the problem remains how to substitute imported food items, such as instant noodles or rice, with local food items.

3 Rationale for selection of the 24-hour recall

A carefully conducted 24-hour recall will give a good estimate of the mean intake of nutrients in a population because people eating more or less than usual will balance each other out. However this also leads to the variability (spread) of intakes on one day being wider than the variability if an average of many days were collected from each person. Given the small size of the Mejjatto population and the desirability of including everyone in the survey, we aimed to collect a single 24-hour recall from all Mejjatto residents to determine the mean intakes. We also measured height and weight of the population as an external validity check of the mean energy intakes. Since the main focus of the project is to determine the variability as accurately as possible, a repeat survey of women 18 years and older was conducted.

4 Mejjatto dietary survey

Twelve members of the Mejjatto community who volunteered to work on the survey were trained during a five day workshop in Majuro, from 10 to 14 May, 1993. The principal trainer was Cecily Dignan, nutritionist with the South Pacific Commission, and she was assisted by Judith Calf, the RMI nutritionist and Ione deBrum, the Food Services Nutrition Educator, Ministry of Social Services RMI.

The training program ensured that the interviewers understood the objectives of the dietary survey; had some grounding in basic nutrition relevant to the Marshall Islands' food culture; developed skills in interviewing techniques; were able to use common food utensils and food models to elicit amounts of food eaten by interviewees; were able to fill-in the dietary questionnaire; and understood the importance of the dietary survey in relation to the Rongelap Resettlement Project as a whole. A detailed description of the diet survey questionnaire, the use of utensils, food models and measures, the recipes and the process of data collection can be found in Appendix A.

Dietary data was collected using a single 24 hour dietary recall on 319 residents, with a repeat 24 hour recall of 48 women 18 years and over, several days after the first dietary recall. The survey was planned so that interviews were spread evenly over the different days of the week, and so that interviewers carried out their interviews in at least two households each day, and attempted to interview a mixture of men, women and children each day. The survey commenced on Saturday 15 May and the first round finished Friday 21 May. The second round, which involved only the women 18 years and over, was carried out on Monday 24 to Wednesday 26 May. The age and sex distribution is shown in Table 1.

Table 1 Description of population and measurements obtained

Age-sex grouping	Weight data	Height data	Diet data	Repeat diet data
Males				
< 5 yrs	20	14	30	-
5 - 9 yrs	28	28	33	-
10 - 17 yrs	36	35	42	-
Females				
< 5 yrs	17	12	26	-
5 - 9 yrs	26	26	30	-
10 - 17 yrs	22	22	26	-
18 - 60 yrs	48	54	54	42
>60 yrs	8	10	10	6

5 Data analysis

The data of the survey was analyzed under the auspices of Dr. Karen Webb, Westmead Hospital NSW, Australia and Dr. Dorothy Mackerras, Dept. of Public Health, Univeristy of Sydney using the Nutritionist IV version 2.0 database. For nutrient information on local foods such as coconuts, the 1983 South Pacific Commission tables were used. A detailed description of the data entry procedures, the food composition data and the coding manual used is found in Appendix A. The data output for all questionnaires is contained in Appendix B.

Table 2 shows the summary of selected results. The mean data for energy intake (EI) as well as consumption of protein, carbohydrates and fat are reasonable if compared, for example, with the reference data in ICRP Publication 23. The average protein intakes of men and women are substantially higher than the US Recommended Dietary Intakes whereas the energy intakes are slightly lower. As expected, intake rates for males are higher than for femaes. The distribution of body mass with mean values of 69.2 kg for males ≥ 18 yrs and of 63.6 kg for females ≥ 18 yrs closely follows a lognormal distribution with $m_m=4.22$ and $m_f=4.14$ and $s_m=0.17$ and $s_f=0.18$.

Table 3 provides an analysis of the observed energy intake rates in comparison to the estimated basal metabolic rate, based on the individual data shown in Figures 1 and 2. The observed mean energy intake for men and women of 1.6 times the estimated mean basal metabolic requirement (BMR_{est}) is consistent with sedentary-light activity. As anticipated, due the spread of distribution is over-disperse with a small number of individuals reporting energy intakes below their estimated basal metabolic rate, whereas the maximum reported energy intake would be equivalent to unrealistically high physical activity levels. A detailed discussion on this subject is contained in Appendix A.

Since reasonable annual mean values are needed for the dose assessment, the variation in intake is described by a lognormal distribution of the ratio of EI/BMR_{est} whereby the standard deviation s of the natural logarithm of the mean m is adjusted such that the 1st percentile of the distribution is equivalent with a ratio of $EI/BMR_{est} = 1$. Since very heavy physical activity is associated with an average daily energy intake of 2.3 EI/BMR_{est} for males and 2.0 for females, the 99th percentile reflects reasonable upper limits of EI/BMR_{est} .

Table 2 Summary of Selected Results from the Mejatto Diet Survey, May 1993
(mean and one standard deviation)

Group	Energy Intake (kcal/d)	Protein Intake (g/d)	Carbohydrate Intake (g/d)	Fat Intake (g/d)
Boys, 10-17 years (N=43)				
mean	2,100 ± 690	87 ± 36	270 ± 100	72 ± 28
Girls, 10-17 years (N=26)				
mean	2,100 ± 570	87 ± 39	280 ± 64	75 ± 26
Men ≥ 18 yrs (N=68)				
mean	2,750 ± 1,200	110 ± 55	365 ± 170	94 ± 52
Women ≥ 18 yrs with one or two recalls (first recall only) (N=64)				
mean	2,000 ± 770	80 ± 43	270 ± 100	71 ± 32
Women ≥ 18 yrs with repeat recalls (N=48)				
1st recall	1,960 ± 690	77 ± 38	260 ± 94	68 ± 27
2nd recall	1,860 ± 590	67 ± 29	250 ± 87	64 ± 25
mean	1,900 ± 500	72 ± 27	255 ± 66	66 ± 21
ICRP 23 reference data for comparison				
adult man	3,000	95	390	120
adult woman	2,100	66	270	85
US RDA (10th edition)				
men 25-50 yrs	2,900	63		
women 25-50 yrs	2,200	50		

Table 3 Energy Intake (EI) compared to the estimated basal metabolic rate (BMR_{est})

Parameter	Boys 10-17 yrs (N=35)	Girls 10-17 yrs (N=22)	Men ≥ 18 yrs (N=53)	Women ≥ 18 yrs (N=41)
observed data:				
EI/ BMR_{est} , avg	1.6	1.7	1.7	1.4
EI/ BMR_{est} , min	0.46	0.69	0.59	0.72
EI/ BMR_{est} , max	2.4	2.5	3.5	2.3
m (EI/ BMR_{est})	0.41	0.51	0.45	0.33
s (EI/ BMR_{est})	0.33	0.32	0.39	0.28
adjusted data:				
m (EI/ BMR_{est})	0.41	0.51	0.45	0.33
s (EI/ BMR_{est})	0.18	0.22	0.19	0.14
EI/ BMR_{est} , 01-percentile	1.0	1.0	1.0	1.0
EI/ BMR_{est} , 50-percentile	1.5	1.7	1.6	1.4
EI/ BMR_{est} , 95-percentile	2.1	2.6	2.3	1.8
EI/ BMR_{est} , 99-percentile	2.3	2.8	2.4	1.9

BMR estimated based on equations by Schoffield et al. (see Appendix A for details).

Figure 1 Energy Intake (EI) compared to the estimated basal metabolic rate (BMR_{est}) for 53 men ≥ 18 yrs: observed distribution based on 24-hr recalls and adjusted lognormal distribution

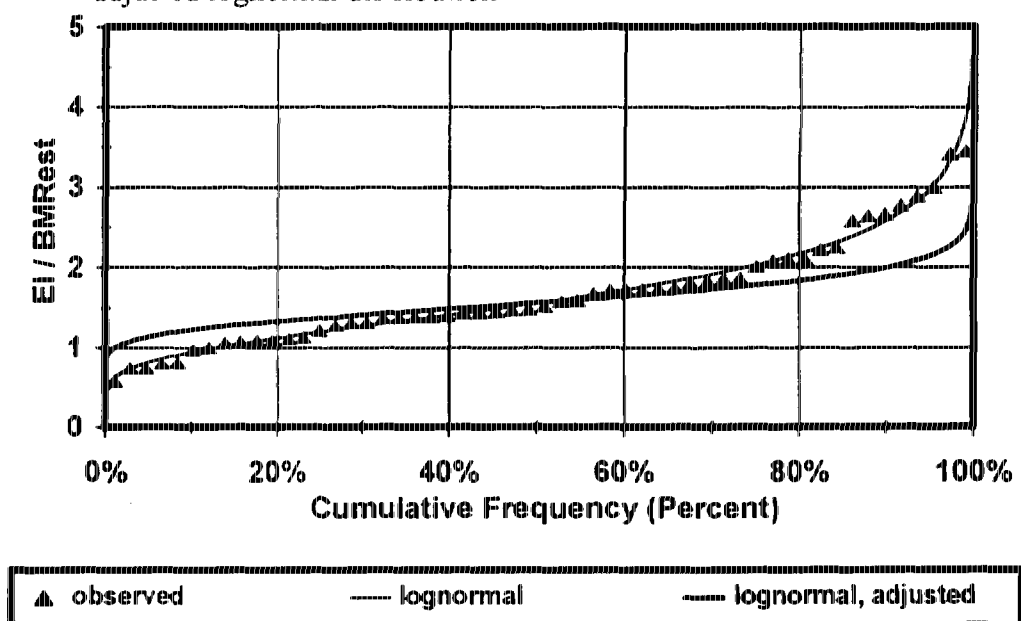
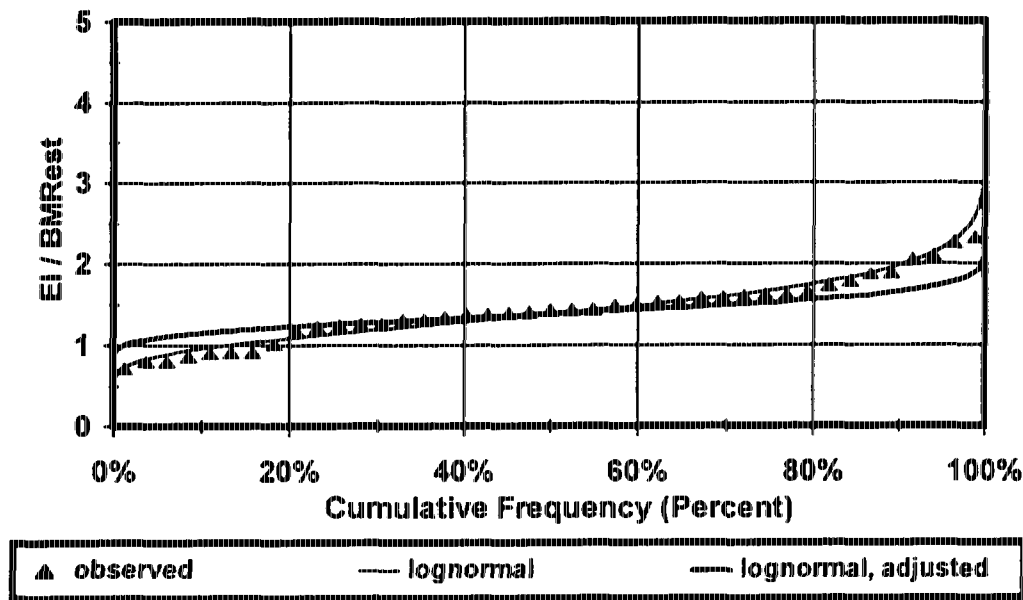


Figure 2 Energy Intake (EI) compared to the estimated basal metabolic rate (BMR_{est}) for 41 women ≥ 18 yrs: observed distribution based repeat 24-hr recalls and adjusted lognormal distribution



6 Determination of a local food only diet for use in radiation dose assessment

One of the greatest challenges in the diet study is the design of a "local food diet". Since there is no established methodology, and the composition of a "local food only" cannot be observed in reality, the following principal objectives were followed:

- (1) The "local food only" diet should be based on the observations of the Mejjatto diet survey as far as energy intake is concerned.
- (2) The "local food only" diet to be established should be realistic with regard to the potential food items available on Rongelap and to the degree that it can sustain an individual by providing the necessary balance of nutrients.
- (3) The selection process of food items should not be biased by availability or non-availability of radionuclide data on the food item.
- (4) Since judgements have to be made in the choices of replacing imported with local food items, the established diets should be laid out in scenarios.
- (5) These scenarios should be presented to the Rongelap community for comment and endorsement in order to fulfill the mandate of the Memorandum of Understanding.

With the endorsement by the Rongelap communities, the following diet scenarios were selected:

- (#1) "Mejatto observed"
The current level of local food items as observed in the Mejatto survey (about 18% of total energy intake)
- (#2) "Mejatto scaled"
Imported food items are replaced by local food items on a calorie-by-calorie basis in the same proportions as these local food items were consumed in the mean on Mejatto during the survey.
- (#3) "Mejatto scaled with rice"
same as #2 but accounting for same mean rice consumption as observed on Mejatto (between 25% and 30% of total energy intake).
- (#4) "Naidu et al., scaled"
Imported food items are replaced by local food items on a calorie-by-calorie basis in the same mean proportions as these local food items were reported in the Naidu et al. survey.¹
- (#5) "Naidu et al., scaled with rice"
same as #4 but accounting for same mean rice consumption as observed on Mejatto (between 25% and 30% of total energy intake).

The resulting diet models for consumption of local foodstuffs are shown in Tables 4 to 7. Table 8 provides a nutritional analysis of the selected diets.

¹ Naidu, J.R., et al. Marshall Islands: A study of diet and living patterns. Brookhaven National Laboratory, Upton, N.Y. July 1980, BNL 51313

Table 4 Food composition for local food diets (Males \geq 18 yrs)

Description	Energy content in food kcal/g	#1 Mejatto observed g/d (avg)	#2 Mejatto scaled w/o rice g/d (avg)	#3 Mejatto scaled with rice g/d (avg)	#4 Naidu et al. scaled w/o rice g/d (avg)	#5 Naidu et al. scaled with rice g/d (avg)
observed in Mejatto survey:						
Bananas (raw, peeled)	0.92	0.0	0.0	0.0	20.3	14.3
Bird, wild, roasted	2.1	14.0	84.7	59.7	5.5	3.9
Coconut Cream (solid)	3.5	64.2	389.1	274.3	0.0	0.0
Coconut Milk (ie diluted cream)	2.5	16.1	97.6	68.8	27.1	19.1
Coconut, drinking, NI	0.11	24.3	147.1	103.7	1014.8	715.5
Coconut Embryo, IU	0.83	1.5	9.0	6.3	330.9	233.3
Coconut hard, WAINI	4.1	5.3	32.3	22.8	176.8	124.7
Coconut soft, MEDE	1.1	5.3	32.1	22.6	256.7	181.0
Coconut crab, blue, boiled	0.85	1.3	7.7	5.4	12.2	8.6
JEKERU, incl. JEKMAI	0.48	83.5	506.5	357.1	372.7	262.7
JEMANIN, (fermented JEKERU)	0.51	3.7	22.4	15.8	0.0	0.0
Pandanus fruit, raw	0.64	12.7	77.2	54.5	135.9	95.8
Pandanus fruit, cooked	0.64	6.1	37.0	26.1	0.0	0.0
Papayas, raw	0.39	6.9	41.7	29.4	32.7	23.1
Pork	3.0	2.7	16.2	11.4	2.3	1.6
Pumpkin	0.20	1.5	9.0	6.3	5.4	3.8
Reef fish (boiled, poached)	1.1	12.9	78.3	55.2	248.2	175.0
Reef fish (grilled, bbq)	1.3	13.2	80.2	56.5	0.0	0.0
Reef fish (pan fried, no flour)	1.1	9.7	59.0	41.6	0.0	0.0
Salt fish (equiv. wet wt.)	1.1	1.6	9.8	6.9	0.0	0.0
Sashimi (tuna, trolling fish)	1.0	7.9	48.1	33.9	0.0	0.0
Tuna, trolling fish (cooked)	1.2	10.6	64.4	45.4	226.3	159.5
Watermelon (raw)	0.32	0.0	0.0	0.0	0.0	0.0
Breadfruit, incl. BWIRO	1.0	0.0	0.0	0.0	222.4	156.8
in Naidu et al. survey, but not observed on Mejatto:						
Coconut, KENAWA	0.1				23.8	16.7
Arrowroot flour	3.6				5.2	3.7
Sweet potatoes	1.1				0.7	0.5
Breadfruit seeds, roasted	2.1				4.0	2.8
Plantains (cooked)	1.2				20.3	14.3
Turtle	0.89				2.0	1.4
Lobster	1.0				1.6	1.1
Clams (giant)	1.5				2.1	1.5
Snails	0.90				30.9	21.8
Octopus	1.6				2.5	1.7
Clams (small)	1.5				5.8	4.1
Jankwon	2.9				32.1	22.6
Chicken	2.4				1.4	1.0
local vegetables	0.35				19.5	13.7

Table 5 Fractional energy intake f_{EI} by food category and diet model
(Males ≥ 18 yrs)

Description	Energy content in food kcal/g	#1 Mejatto observed f_{EI}	#2 Mejatto scaled w/o rice f_{EI}	#3 Mejatto scaled with rice f_{EI}	#4 Naidu et al. scaled w/o rice f_{EI}	#5 Naidu et al. scaled with rice f_{EI}
observed in Mejatto survey:						
Bananas (raw, peeled)	0.92	0.0	0.0	0.0	6.8E-03	4.8E-03
Bird, wild, roasted	2.1	1.1E-02	6.6E-02	4.6E-02	4.3E-03	3.0E-03
Coconut Cream (solid)	3.5	8.1E-02	4.9E-01	3.4E-01	0.0	0.0
Coconut Milk (ie diluted cream)	2.5	1.5E-02	8.9E-02	6.3E-02	2.5E-02	1.7E-02
Coconut, drinking, NI	0.11	9.7E-04	5.9E-03	4.1E-03	4.1E-02	2.9E-02
Coconut Embryo, IU	0.83	4.5E-04	2.7E-03	1.9E-03	1.0E-01	7.0E-02
Coconut hard, WAINI	4.1	8.0E-03	4.8E-02	3.4E-02	2.6E-01	1.9E-01
Coconut soft, MEDE	1.1	2.0E-03	1.2E-02	8.7E-03	9.9E-02	7.0E-02
Coconut crab, blue, boiled	0.85	3.9E-04	2.4E-03	1.7E-03	3.8E-03	2.7E-03
JEKERU, incl. JEKMAI	0.48	1.5E-02	8.9E-02	6.2E-02	6.5E-02	4.6E-02
JEMANIN, (fermented JEKERU)	0.51	6.9E-04	4.2E-03	2.9E-03	0.0	0.0
Pandanus fruit, raw	0.64	3.0E-03	1.8E-02	1.3E-02	3.1E-02	2.2E-02
Pandanus fruit, cooked	0.64	1.4E-03	8.6E-03	6.1E-03	0.0	0.0
Papayas, raw	0.39	9.7E-04	5.9E-03	4.2E-03	4.6E-03	3.3E-03
Pork	3.0	3.0E-03	1.8E-02	1.3E-02	2.5E-03	1.8E-03
Pumpkin	0.20	1.1E-04	6.5E-04	4.6E-04	4.0E-04	2.8E-04
Reef fish (boiled, poached)	1.1	5.1E-03	3.1E-02	2.2E-02	9.7E-02	6.9E-02
Reef fish (grilled, bbq)	1.3	6.2E-03	3.8E-02	2.6E-02	0.0	0.0
Reef fish (pan fried, no flour)	1.1	5.7E-03	3.5E-02	2.5E-02	0.0	0.0
Salt fish (equiv. wet wt.)	1.1	6.4E-04	3.9E-03	2.7E-03	0.0	0.0
Sashimi (tuna, trolling fish)	1.0	3.0E-03	1.8E-02	1.3E-02	0.0	0.0
Tuna, trolling fish (cooked)	1.2	4.6E-03	2.8E-02	2.0E-02	9.7E-02	6.9E-02
Watermelon (raw)	0.32	0.0	0.0	0.0	0.0	0.0
Breadfruit, incl. BWIRO	1.0	0.0	0.0	0.0	8.3E-02	5.9E-02
in Naidu et al. survey, but not observed on Mejatto:						
Coconut, KENAWA	0.1	0.0	0.0	0.0	8.6E-04	6.1E-04
Arrowroot flour	3.6	0.0	0.0	0.0	6.8E-03	4.8E-03
Sweet potatoes	1.1	0.0	0.0	0.0	2.9E-04	2.0E-04
Breadfruit seeds, roasted	2.1	0.0	0.0	0.0	3.1E-03	2.2E-03
Plantains (cooked)	1.2	0.0	0.0	0.0	8.6E-03	6.0E-03
Turtle	0.89	0.0	0.0	0.0	6.6E-04	4.7E-04
Lobster	1.0	0.0	0.0	0.0	5.7E-04	4.0E-04
Clams (giant)	1.5	0.0	0.0	0.0	1.1E-03	7.9E-04
Snails	0.90	0.0	0.0	0.0	1.0E-02	7.1E-03
Octopus	1.6	0.0	0.0	0.0	1.5E-03	1.0E-03
Clams (small)	1.5	0.0	0.0	0.0	3.1E-03	2.2E-03
Jankwon	2.9	0.0	0.0	0.0	3.4E-02	2.4E-02
Chicken	2.4	0.0	0.0	0.0	1.2E-03	8.4E-04
local vegetables	0.35	0.0	0.0	0.0	2.5E-03	1.8E-03

Table 6 Food composition for local food diets (Females ≥ 18 yrs)

Description	Energy content in food kcal/g	#1 Mejatto observed g/d (avg)	#2 Mejatto scaled w/o rice g/d (avg)	#3 Mejatto scaled with rice g/d (avg)	#4 Naidu et al. scaled w/o rice g/d (avg)	#5 Naidu et al. scaled with rice g/d (avg)
observed in Mejatto survey:						
Bananas (raw, peeled)	0.92	2.4	12.9	9.7	14.1	10.6
Bird, wild, roasted	2.1	1.6	8.8	6.6	3.8	2.9
Coconut Cream (solid)	3.5	45.4	246.0	185.1	0.0	0.0
Coconut Milk (ie diluted cream)	2.5	7.6	40.9	30.8	18.8	14.2
Coconut, drinking, NI	0.11	37.1	200.9	151.1	702.6	530.5
Coconut Embryo, IU	0.83	0.5	2.8	2.1	229.1	173.0
Coconut hard, WAINI	4.1	6.0	32.7	24.6	122.4	92.4
Coconut soft, MEDE	1.1	0.4	2.2	1.6	177.7	134.2
Coconut crab, blue, boiled	0.85	0.0	0.0	0.0	8.5	6.4
JEKERU, incl. JEKMAI	0.48	53.4	289.5	217.8	258.0	194.8
JEMANIN, (fermented JEKERU)	0.51	0.0	0.0	0.0	0.0	0.0
Pandanus fruit, raw	0.64	24.2	130.9	98.4	94.1	71.0
Pandanus fruit, cooked	0.64	11.6	63.0	47.4	0.0	0.0
Papayas, raw	0.39	12.3	66.8	50.2	22.7	17.1
Pork	3.0	2.2	11.7	8.8	1.6	1.2
Pumpkin	0.20	2.1	11.6	8.7	3.8	2.8
Reef fish (boiled, poached)	1.1	10.3	55.8	41.9	171.9	129.8
Reef fish (grilled, bbq)	1.3	3.5	18.7	14.1	0.0	0.0
Reef fish (pan fried, no flour)	1.1	28.4	153.6	115.6	0.0	0.0
Salt fish (eqv. wet wt.)	1.1	3.7	19.9	15.0	0.0	0.0
Sashimi (tuna, trolling fish)	1.0	0.5	3.0	2.2	0.0	0.0
Tuna, trolling fish (cooked)	1.2	3.8	20.4	15.3	156.7	118.3
Watermelon (raw)	0.32	4.4	24.0	18.1	0.0	0.0
Breadfruit incl. BWIRO	1.0	22.6	122.3	92.0	153.9	116.2
in Naidu et al. survey, but not observed on Mejatto:						
Coconut, KENAWA	0.1				16.4	12.4
Arrowroot flour	3.6				3.6	2.7
Sweet potatoes	1.1				0.5	0.4
Breadfruit seeds, roasted	2.1				2.8	2.1
Plantains (cooked)	1.2				14.0	10.6
Turtle	0.89				1.4	1.1
Lobster	1.0				1.1	0.8
Clams (giant)	1.5				1.4	1.1
Snails	0.9				21.4	16.1
Octopus	1.6				1.7	1.3
Clams (small)	1.5				4.0	3.1
Jankwon	2.9				22.2	16.8
Chicken	2.4				1.0	0.7
local vegetables	0.35				13.5	10.2

Table 7 Fractional energy intake f_{EI} by food category and diet model
(Females ≥ 18 yrs)

Description	Energy content in food kcal/g	#1 Mejatto observed f_{EI}	#2 Mejatto scaled w/o rice f_{EI}	#3 Mejatto scaled with rice f_{EI}	#4 Naidu et al. scaled w/o rice f_{EI}	#5 Naidu et al. scaled with rice f_{EI}
observed in Mejatto survey:						
Bananas (raw, peeled)	0.92	1.1E-03	6.2E-03	4.7E-03	6.8E-03	5.1E-03
Bird, wild, roasted	2.1	1.8E-03	9.8E-03	7.4E-03	4.3E-03	3.2E-03
Coconut Cream (solid)	3.5	8.2E-02	4.5E-01	3.4E-01	0.0	0.0
Coconut Milk (ie diluted cream)	2.5	1.0E-02	5.4E-02	4.1E-02	2.5E-02	1.9E-02
Coconut, drinking, NI	0.11	2.1E-03	1.2E-02	8.7E-03	4.1E-02	3.1E-02
Coconut Embryo, IU	0.83	2.2E-04	1.2E-03	9.2E-04	1.0E-01	7.5E-02
Coconut hard, WAINI	4.1	1.3E-02	7.1E-02	5.3E-02	2.6E-01	2.0E-01
Coconut soft, MEDE	1.1	2.2E-04	1.2E-03	9.0E-04	9.9E-02	7.5E-02
Coconut crab, blue, boiled	0.85	0.0	0.0	0.0	3.8E-03	2.9E-03
JEKERU, incl. JEKMAI	0.48	1.3E-02	7.3E-02	5.5E-02	6.5E-02	4.9E-02
JEMANIN, (fermented JEKERU)	0.51	0.0	0.0	0.0	0.0	0.0
Pandanus fruit, raw	0.64	8.1E-03	4.4E-02	3.3E-02	3.1E-02	2.4E-02
Pandanus fruit, cooked	0.64	3.9E-03	2.1E-02	1.6E-02	0.0	0.0
Papayas, raw	0.39	2.5E-03	1.4E-02	1.0E-02	4.6E-03	3.5E-03
Pork	3.0	3.4E-03	1.9E-02	1.4E-02	2.5E-03	1.9E-03
Pumpkin	0.20	2.2E-04	1.2E-03	9.1E-04	4.0E-04	3.0E-04
Reef fish (boiled, poached)	1.1	5.8E-03	3.2E-02	2.4E-02	9.7E-02	7.3E-02
Reef fish (grilled, bbq)	1.3	2.3E-03	1.3E-02	9.5E-03	0.0	0.0
Reef fish (pan fried, no flour)	1.1	1.6E-02	8.7E-02	6.5E-02	0.0	0.0
Salt fish (equiv. wet wt.)	1.1	2.1E-03	1.1E-02	8.6E-03	0.0	0.0
Sashimi (tuna, trolling fish)	1.0	3.0E-04	1.6E-03	1.2E-03	0.0	0.0
Tuna, trolling fish (cooked)	1.2	2.3E-03	1.3E-02	9.5E-03	9.7E-02	7.3E-02
Watermelon (raw)	0.32	7.5E-04	4.0E-03	3.0E-03	0.0	0.0
Breadfruit, incl. BWIRO	1.0	1.2E-02	6.6E-02	5.0E-02	8.3E-02	6.3E-02
in Naidu et al. survey, but not observed on Mejatto:						
Coconut, KENAWA	0.1	0.0	0.0	0.0	8.6E-04	6.5E-04
Arrowroot flour	3.6	0.0	0.0	0.0	6.8E-03	5.2E-03
Sweet potatoes	1.1	0.0	0.0	0.0	2.9E-04	2.2E-04
Breadfruit seeds, roasted	2.1	0.0	0.0	0.0	3.1E-03	2.3E-03
Plantains (cooked)	1.2	0.0	0.0	0.0	8.6E-03	6.5E-03
Turtle	0.89	0.0	0.0	0.0	6.6E-04	5.0E-04
Lobster	1.0	0.0	0.0	0.0	5.7E-04	4.3E-04
Clams (giant)	1.5	0.0	0.0	0.0	1.1E-03	8.4E-04
Snails	0.90	0.0	0.0	0.0	1.0E-02	7.6E-03
Octopus	1.6	0.0	0.0	0.0	1.5E-03	1.1E-03
Clams (small)	1.5	0.0	0.0	0.0	3.1E-03	2.4E-03
Jankwon	2.9	0.0	0.0	0.0	3.4E-02	2.6E-02
Chicken	2.4	0.0	0.0	0.0	1.2E-03	9.0E-04
local vegetables	0.35	0.0	0.0	0.0	2.5E-03	1.9E-03

Table 8 Key data for diet models to be used in Rongelap compliance assessment
(data for females >18 yrs; *data for males >18 yrs in italics*)

Parameter	#1 Mejatto	#2 Mejatto scaled w/o rice	#3 Mejatto scaled with rice	#4 Naidu et al. scaled w/o rice	#5 Naidu et al. scaled with rice
Total Energy Intake (kcal/d)	1,900 2,750	1,900 2,750	1,900 2,750	1,900 2,750	1,900 2,750
Energy Intake from Local Foodstuffs (Percent)	18% 17%	100% 100%	75% 70%	100% 100%	75% 70%
Energy Intake from Rice (Percent)	25% 30%	0% 0%	25% 30%	0% 0%	25% 30%
Protein Intake (g/d)	72 110	82 130	71 110	100 150	87 120
Carbohydrate Intake (g/d)	260 360	140 130	210 260	180 260	240 360
Fat Intake (g/d)	67 95	120 200	92 130	80 120	61 83

7 Sensitivity analysis

In a series of meetings with the Rongelap communities on Mejatto, Ebeye and Majuro in February 1994, the following suggestions were made:

- (1) To include well water intake in dose assessment
- (2) To vary the consumption of coconut crabs (up to 2 crabs per day, equivalent to about 80 g/d)
- (3) To vary the consumption of arrowroot flour (up to 50 g/d)
- (4) To vary the consumption of wild birds (say 5 times the amount in the diets)
- (5) To vary the consumption of bananas, chicken, and pumpkin
- (6) To include the ingestion of medicinal plants

It is also suggested that well water consumption be considered in the dose assessment and that sensitivity calculations be performed to evaluate the variance in higher intakes of coconut crabs, arrowroot flour, wild birds, bananas, chicken, and pumpkin by increasing the uptake rate tenfold with corresponding reductions in the remaining food for a given energy intake level. A separate sensitivity analysis can be made for medicinal plant intake. In addition, calculations local food consumption in between the intake observed on Mejatto and a 100% level were requested by the communities. However, the Diet #2 ("Mejatto scaled") was endorsed as the basis for the dose assessment.

APPENDIX 5

PART A:

A PROSPECTIVE DOSE ASSESSMENT FOR THE RONGELAP RESETTLEMENT
PROJECT: Methodology and Results of Determination of Compliance with the Limit for
Whole-Body Radiation Dose Equivalent (S. L. Simon)

PART B:

AN ANALYSIS OF RADIATION DOSES THAT COULD BE RECEIVED
SUBSEQUENT TO THE RESETTLEMENT OF RONGELAP (M. C. Thorne)

PART C:

EXTRAPOLATING FUTURE DOSES FOR RONGELAP FROM 1958-1964 WHOLE
BODY COUNTING (B. Franke)

A PROSPECTIVE DOSE ASSESSMENT FOR THE
RONGELAP RESETTLEMENT PROJECT:
Methodology and Results of Determination of Compliance with the Limit for
Whole-Body Radiation Dose Equivalent

S. L. Simon
RMI Nationwide Radiological Study

BACKGROUND

A four-way Memorandum of Understanding (MOU) was signed between the Republic of the Marshall Islands Government, the Rongelap Atoll Local Government, the U.S. Department of Energy (Office of Environment, Safety and Health) and the U.S. Department of Interior (Office of Territorial and International Affairs) on 2 February 1992. The agreement, a development of the provisions of U.S. Public Law 99-239 and Nitijela Resolution 1986-62, enacted two limits which must be determined to be in compliance before resettlement of Rongelap should take place. The determination of compliance was the central objective of studies funded by the U.S. Department of Interior to the scientific study entitled, the Rongelap Resettlement Project.

The first of the limits refers to the the total whole body radiation dose equivalent, a combination of internal dose resulting from the intake of locally grown foods and external-dose resulting from exposure due to radioactivity resident in the soil.

As stated in ARTICLE II, Section 2:

"The primary condition of a determination to initiate resettlement for the area defined in Section 1 [Rongelap Island and those islands comprising the southern one-half of Rongelap Atoll, on the western side of Rongelap Atoll from Bokonlep Island south, on the eastern side of Rongelap Atoll, from Erebot Islands south] of this Article is that the calculated maximum whole body radiation dose equivalent to the maximally exposed resident shall not exceed 100 mrem (mrem)/year above natural background, based upon a local food only diet..."

METHODOLOGICAL APPROACH

The basic concept for determining compliance was to: (1) perform measurements from which the external exposure-rate on Rongelap Island could be determined, (2) measure the radioactivity in foods from Rongelap Island, (3) assemble a description of a reasonable local-food only diet (and several variations) to which the community agreed, (4) predict the whole body absorbed dose using the external exposure-rate, radioactivity in foods and dietary descriptions, (5) combine the estimates of internal and external dose, and (6) compare the result to the stated limit. These

various activities were undertaken by the Rongelap Resettlement Project and are reported on in several sections of this report.

Prospective dose assessment calculations (items 4 through 6 above) were conducted in this investigation by a Monte Carlo algorithm. This method produced dose estimates from a varied combination of food intake-rates, plant uptake factors, and contamination levels on different areas of the island. The endpoint is a distribution of doses which may occur among members of the Rongelap community as a result of differing body sizes, intake rates and locations for collecting food.

In the calculations reported here, little attention is given to subjective estimates of parameter uncertainty. The Monte Carlo algorithm is mainly for the purpose of simulating natural variability in body mass of residents, radioactivity concentrations and food-intake rates. It is assumed for these purposes that the diets as described by the community are an accurate assessment of their intended lifestyle(s). The distribution of body sizes is used to predict a distribution of energy intake-rates (kcal/y). The caloric intake is apportioned into mass intakes of locally grown foods according to the dietary descriptions described elsewhere in this report. The endpoint, therefore, is a deterministic estimate of each quantile of the population dose distribution. It is important to understand the endpoint is not an uncertainty distribution for the dose for any single individual.

It is acknowledged here that there is considerable uncertainty in many aspects of the dose calculations. Because of this uncertainty, it is difficult to determine, and impossible to prove, whether any individual will exceed the specified limit in the future. Yet, this determination is made here in the same spirit in which it was envisioned and stated in the MOU. The simplistic philosophy in which the MOU limit is stated implies that a credible estimate of dose is sufficient for the purposes of determining compliance. A scientifically credible estimate in our opinion is based, to the degree possible, first on quantitative measurement data (e.g. measurements of radioactivity), secondly, on expert observation (e.g. conducting interviews on dietary habits), and thirdly, on expert opinion (e.g., the community's evaluation of the diet). These criteria have been assured by: (i) the process of objective and state-of-the-art radioactivity measurements, (ii) verification of measurements by split-sample analysis with other laboratories, (iii) extensive consultation with the Rongelap community, (iv) external peer review, and (v) independent and redundant dose computations to assure accuracy in calculations.

Assumptions

As in any assessment, a number of assumptions are required. Some important assumptions are mentioned here.

(1) In-situ measurements of ^{137}Cs from a systematic sampling plan are used directly, in this assessment i.e., no spatial averaging is used. The effect of this methodological decision is to implicitly assume that obtained measurements of radioactivity are representative of the local radiation environment on a scale of 200 m. The distribution of in-situ measured count-rates from

^{137}Cs are used to directly or indirectly predict: (1) a distribution of external exposure-rates, (2) a distribution of soil areal inventory (Bq/m^2 ^{137}Cs) values, (3) a distribution of soil concentrations (Bq/kg ^{137}Cs), and (4) the ^{137}Cs concentration in foods using plant to soil concentration ratios, specific for different plant foods.

Although there are only 63 different sampling cells on the island, the distribution of count-rates is assumed as continuous, rather than discrete. Thus, the possible count-rate values which are selected by the Monte Carlo algorithm during the 1000 iterations represent all values between the minimum and maximum truncation points. The count-rate values (each resulting in a unique contamination level) are matched with the characteristics of a selected hypothetical community member. The result of this method is that the complete distribution of caloric intake-rates are randomly matched with the complete distribution of radioactivity levels.

(2) Five dietary models (see Appendix A4) have been provided for simulation. These models are assumed in this context to be relatively precise descriptions of five alternative lifestyle choices for Rongelap community members. The diets are used in this assessment without consideration of uncertainty. Simulation of only natural parameter variability is attempted. Briefly, the five diets describe the following scenarios:

- Diet 1 - The current mixture of local food as observed during a survey of the Rongelap community on Mejjatto. The diet includes approximately 18% local food (by caloric value), the rest is provided by rice and other imports.
- Diet 2 - Local food only diet. Rice and other imports are eliminated. The relative mixture of local foods is maintained; their quantities are increased so as the total caloric value equals the observed energy intake on Mejjatto.
- Diet 3 - Same as Diet 2 except rice is included in the same quantity as now observed on Mejjatto.
- Diet 4 - Naidu (1980) diet without rice. Imports of diet 1 are replaced with local food items as observed by Naidu.
- Diet 5 - Naidu diet including rice in the same quantity as now observed on Mejjatto, local food items are reduced proportionately.

(3) Specified relationships between parameters is maintained according to dietary literature and a well defined assessment protocol (Appendix A2). Important assumptions and relationships are briefly noted below.

- The body mass is randomly drawn from a distribution of body sizes specific for each sex. This distribution is described in an accompanying section on diet study results.
- The basal metabolic rate (BMR) is predicted from an empirical relationship derived from the literature and the sampled body mass.
- The ratio of energy intake to basal metabolic rate (EI/BMR) is randomly drawn from a sex-specific distribution derived from data of a study of dietary habits of the Mejjatto community.

- The energy intake (kcal/d) is predicted from the product of BMR x EI/BMR. Note that EI/BMR is randomly determined and BMR is determined from a functional expression which is dependent on a random quantity (body mass).
- The energy intake (EI) is used to determine the total mass of foods eaten such that the total energy intake of the foods in the simulation equals the sampled value of EI, the relative apportionment of food types is set deterministically by the dietary description.
- The in-situ measured ^{137}Cs count-rate is randomly drawn from a distribution describing the empirical in-situ measurement data from the survey of Rongelap Island.
- The soil concentration (Bq/kg) and external exposure-rate are determined deterministically from the sampled count-rate. Both are proportional to the count-rate.
- The intake of radioactivity (Bq/y) from each food product is determined from the product of the food intake-rate and the radioactivity concentrations (Bq/y = g/d x Bq/g). The total intake of radioactivity is calculated from considering all the relevant food types.
- The external dose is determined from the calculated exposure-rate. The internal dose is calculated from the dietary description and calculated radioactivity intakes. The total dose equivalent is determined from a summation of external and internal exposure.

(4) The concentrations of ^{137}Cs in foods are predicted from a distribution of the plant/soil concentration ratio (CR) for each plant type (described in more detail in a later section). This distribution approximately describes expected natural variations in CR values that have been observed.

(5) The conversion coefficients for effective dose equivalent per unit external exposure (Sv/R) are energy dependent values described by ICRP (1987). The conversion coefficients for effective dose equivalent per unit intake of ^{137}Cs (Sv/Bq) are age-dependent values described by ICRP (1989).

(6) Only the radiation dose (external plus internal) from ^{137}Cs was explicitly determined in this assessment. As described in other sections, there are measurable quantities of ^{241}Am , ^{60}Co and $^{239,240}\text{Pu}$ in the environment at Rongelap as well as ^{90}Sr (which was not measured). However, results from the assessment of ^{137}Cs alone have proved to provide sufficient information for the determination of compliance.

Input Data

The input values for the dosimetry calculations are drawn from probability distributions by the Monte Carlo sampling method. The parameters describing the probability distributions are shown in Table A5.1. The mean and variance of the distributions were determined from the original empirical data. The only exception was for EI/BMR for which the variance was adjusted

as described in the accompanying report on the dietary survey. All distributions endpoints were truncated at $\pm 3\sigma$ unless noted otherwise.

One of the most important input parameters is the count-rate of ^{137}Cs which determines external exposure-rate, soil concentration and plant contamination. Values for in-situ count rate for ^{137}Cs were drawn from a truncated normal distribution with the following parameters: $\bar{x} = 6.97$ c/s, $\sigma = 2.91$ c/s, minimum = 0.26 c/s, and maximum = 15.6 c/s. This moments of the distribution was determined directly from the in-situ measurements made on the 200 m grid. The adequacy of fit to a normal distribution was excellent as determined by probability plotting.

The parameters for lognormal distributions for plant:soil concentration ratios (CR values) were determined using literature data and judgement. The mean value was derived directly from the literature. An assumption was made that the relative variability (geometric standard deviation or GSD) was 1.5. This implies that the 95% confidence bounds on the median are approximately 0.44 times lower ($\frac{1}{\text{GSD}^2}$) to 2.25 times higher (GSD^2). The standard deviation (Aitchison and Brown 1969) was then determined as:

$$s = [\exp(2\mu + \sigma^2) \times (\exp(\sigma^2) - 1)]^{1/2}$$

Similarly, the median (geometric mean or GM) was determined (again see Aitchison and Brown (1969) as:

$$\text{GM} = \exp(\mu) \text{ where,}$$

$$\mu = \ln \left[\frac{\bar{x}}{1 + (s/\bar{x})^2} \right]^{1/2}.$$

Table A5.1 Parameters of probability (variability) distributions for Monte Carlo calculations

Model Parameter	Distribution Type	\bar{x}	standard deviation	GM	GSD	minimum	maximum
BM male	lognormal	69.02	11.82	68.03	1.19	49.58	95.91
BM female	lognormal	63.83	11.58	62.80	1.20	41.11	878.84
EI/BMR male	lognormal	1.60	0.31	1.57	1.21	0.89	2.77
EI/BMR female	lognormal	1.40	0.20	0.91	1.15	0.92	2.11
in-situ count rate	normal	6.87	2.91			0.25	14.52
Banana (CR)	lognormal	7.00E-02	2.95E-02	6.50E-02	1.5	0	0.22
Bird (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.0021
Coconut cream (CR)	lognormal	3.00E-01	1.26E-01	2.75E-01	1.5	0	0.90
Coconut milk (CR)	lognormal	1.50E-01	6.32E-02	1.38E-01	1.5	0	0.46
Coconut ni (CR)	lognormal	1.30E-01	5.47E-02	1.20E-01	1.5	0	0.40
Coconut iu (CR)	lognormal	3.00E-01	1.26E-01	2.75E-01	1.5	0	0.91
Coconut waini (CR)	lognormal	3.00E-01	1.26E-01	2.75E-01	1.5	0	0.91
Coconut mede (CR)	lognormal	2.00E-01	8.42E-02	1.85E-01	1.5	0	0.61
Coconut crab (CR)	lognormal	2.00E-01	8.42E-02	1.85E-01	1.5	0	0.61
Jekeru (CR)	lognormal	3.00E-01	1.26E-01	2.75E-01	1.5	0	0.91
Jemanin (CR)	lognormal	3.00E-01	1.26E-01	2.75E-01	1.5	0	0.91
Pandanus raw (CR)	lognormal	3.50E-01	2.11E-01	3.01E-01	1.5	0	1.56
Pandanus cooked (CR)	lognormal	3.50E-01	2.11E-01	3.01E-01	1.5	0	1.56
Papaya (CR)	lognormal	3.50E-01	2.11E-01	3.30E-01	1.5	0	1.56
Pork (conc.)	lognormal	3.44E-01	1.45E-01	3.17E-01	1.5	0	1.04
Pumpkin (CR)	lognormal	3.50E-01	1.47E-01	3.23E-01	1.5	0	1.07
Reef fish boiled (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Reef fish grill (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Reef fish fried (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Salt fish (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Sashimi (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Tuna cooked (conc.)	lognormal	6.54E-04	2.75E-04	6.00E-04	1.5	0	0.002
Watermelon (CR)	lognormal	3.50E-01	2.11E-01	3.01E-01	1.5	0	1.56
Breadfruit (CR)	lognormal	2.00E-01	1.85E-01	8.42E-02	1.5	0	0.61

Functional Relationships

Some requisite parameters for the dose assessment calculations are calculated from other model parameters. This includes: basal metabolic rate (BMR calculated from body mass), energy intake (EI calculated from EI/BMR and BMR) and Sv/Bq (calculated from body mass). These functional relationships are noted below.

$$(i) \text{ BMR} = \alpha + (\beta \times \text{BM})$$

where,

BMR = basal metabolic rate

BM = body mass (kg)

α , β are constants obtained from Warwick (1989, see below)

	α (kcal/d)	β (kcal/d/kg)
Females	486.4	14.81
Males	691.8	15.05

$$(ii) \text{ EI} = \text{BRM} \times \text{EI/BMR}$$

where,

EI = energy intake (kcal/y)

BRM = basal metabolic rate (see item 'i' above)

EI/BMR = energy intake per basal metabolic rate (a sampled parameter, see Table A5.1)

$$(iii) \text{ Sv/Bq} = m_0 + (m_1 \times \text{BM}) + (m_2 \times \text{BM}^2) + (m_3 \times \text{BM}^3) + (m_4 \times \text{BM}^4)$$

where,

BM = body mass (kg, a sampled parameter, see Table A5.1)

$$m_0 = 2.6 \times 10^{-8}$$

$$m_1 = 2.3 \times 10^{-9}$$

$$m_2 = 9.3 \times 10^{-11}$$

$$m_3 = 1.4 \times 10^{-12}$$

$$m_4 = 7.5 \times 10^{-15}$$

$$(iv) \text{ Bq/g } (^{137}\text{Cs in plant foods}) = \text{CR} \times \text{Bq/g } (^{137}\text{Cs in soil})$$

where,

$$\text{CR} = \text{plant:soil concentration ratio ([Bq g}^{-1} \text{ plant material] / [Bq g}^{-1} \text{ soil])}$$

RESULTS OF CALCULATIONS

Model calculations of external dose were deterministically related to in-situ count rate and did not exhibit any variability. Internal dose, however, exhibited variability for equal ground contamination as a result of simulating variability of individual energy intakes and plant:soil CR values. Figure 1 shows, for example, the degree of variability predicted for internal dose as a function of in-situ count-rate of ^{137}Cs .

Table A5.2 provides summary statistics of the total dose distributions (external plus internal dose) calculated separately for men and women for five different model diets. The table clearly indicates that all diets other than the Mejatto diet are substantially over the compliance limit for a significant portion of the adult population. The Mejatto diet which incorporates only 18% locally grown foods had a median dose of 28 to 29 mrem/y and a maximum of 74 to 92 mrem/y.

Figures 2 and 3 show the cumulative distribution functions of external dose, internal dose and total dose equivalent-rate (mrem/y from ^{137}Cs) for Diet 1, women and men, respectively.

Figures 4 and 5 show the cumulative distribution functions of total dose equivalent-rate (external plus internal, mrem/y from ^{137}Cs) as determined from the Monte Carlo simulations of the five diets for women and men, respectively.

Table A5.2 Summary statistics of Monte Carlo simulations for prospective Rongelap dose assessment. Values are effective dose equivalent (mrem/y, external plus internal) from ^{137}Cs .

FEMALE ADULT	Diet 1 (mrem/y)	Diet 2 (mrem/y)	Diet 3 (mrem/y)	Diet 4 (mrem/y)	Diet 5 (mrem/y)
Minimum	0.76	4.06	6.71	3.07	2.33
Maximum	74.04	462.20	222.21	565.59	306.53
number of simulations	1000	1000	1000	1000	1000
Mean	28.20	116.25	87.71	134.79	98.28
Median	28.18	110.53	86.79	126.08	95.06
Standard deviation	12.43	53.64	37.00	67.86	43.47
Std Error	0.39	1.70	1.17	2.15	1.37
Skewness	0.27	0.99	0.37	1.19	0.45
Proportion in excess of 100 mrem/y	0%	60%	35%	68%	46%

MALE ADULT	Diet 1 (mrem/y)	Diet 2 (mrem/y)	Diet 3 (mrem/y)	Diet 4 (mrem/y)	Diet 5 (mrem/y)
Minimum	1.09	8.29	3.88	2.90	1.43
Maximum	92.07	696.67	474.48	1002.08	871.75
Number of simulations	1000	1000	1000	1000	1000
Mean	29.22	136.96	98.167	190.34	140.40
Median	28.43	124.72	94.10	170.88	134.24
Standard deviation	13.42	78.64	46.87	111.34	72.99
Variance	180.01	6183.92	2196.43	12396.32	5327.72
Standard error	0.42	2.49	1.48	3.52	2.31
Proportion in excess of 100 mrem/y	0%	65%	45%	82%	71%

SENSITIVITY ANALYSIS

The simulation results were examined to determine to source of the variations in the prediction of internal dose. Such an examination is termed a sensitivity analysis. The sensitivity analysis is limited in its ability to draw conclusions by the level of detail present in the model. The results of the sensitivity analysis relate only to the parameters included in the model, their assigned probability distributions, and the mathematical form of the model.

The simplest form of sensitivity analysis conducted was a determination of Pearson product moment correlation coefficients between the output variable (internal dose equivalent) and the input variables. These coefficients are shown in the first column of the Table A5.3. As is shown, those parameters which are correlated with Internal Dose are External Dose (because it is proportional to the soil concentration), Body Mass (it determines caloric intake), the dose conversion factor (Sv/Bq, this is dependent on body mass), the external exposure-rate (also proportional to soil concentration), soil concentration (it determines the uptake into food crops), counts per second of the in-situ detector, the concentration ratio (CR) of various foods (e.g., coconut cream, diluted coconut cream, drinking ni, iu, mede, jekeru, pandanus, papaya, breadfruit), the basal metabolic rate and the energy intake.

Correlations between other parameters are also shown. Many of the other correlation between parameter values are close to zero. This provides confirmation that spurious, unintended correlations between parameters did not result from the Monte Carlo selection process. Zero correlations, for example, were intended between the CR values for different food crops. This properly simulates the independence of individual plant species. Intentional correlations can be added as needed, however, in general, their effect is not great, nor is there often a legitimate rationale for adding them.

A few legitimate correlations are to be noted, however. For example, body mass (kg) and the dose conversion factor (Sq/Bq) are moderately correlated with a value of 0.4; body mass or basal metabolic rate (BMR) was correlated with energy intake (EI) with a value of 0.63.

Table A5.3. Pearson product moment correlations of model parameters determined from Monte Carlo simulations

	Dose internal	Dose Ext.	Dose Total	Body Mass	Sv/Bq	Exp-rate
Dose Internal	1					
Dose External	0.792	1				
Dose Total	0.999	0.813	1			
Body mass	0.353	0.086	0.342	1		
Sv/Bq	0.219	0.012	0.209	0.393	1	
Exp-rate	0.792	1	0.813	0.086	0.012	1
Bq/g soil	0.792	1	0.813	0.086	0.012	1
counts per sec	0.792	1	0.813	0.086	0.012	1
CR coconut cream	0.269	0.066	0.26	0.055	-0.052	0.066
CR dilute cream	-0.043	-0.038	-0.044	-0.132	-0.06	-0.038
CR ni	0.214	0.167	0.213	-0.03	0.031	0.167
CR iu	0.105	0.07	0.104	-0.045	-0.032	0.07
CR waini	0.083	0.035	0.082	-0.034	0.053	0.035
CR mede	0.011	-0.047	0.008	0.011	-0.016	-0.047
CR jekeru	0.301	-0.038	0.285	0.156	0.069	-0.038
CR pandanus raw	0.240	0.046	0.231	0.015	0.027	0.046
CR pandanus cooked	0.118	-0.006	0.112	0.048	-0.063	-0.006
CR papaya	0.084	0.077	0.084	-0.161	-0.148	0.077
CR breadfruit	0.157	0.154	0.159	-0.062	0.062	0.154
BMR female	0.353	0.086	0.342	1	0.393	0.086
EI female	0.508	0.128	0.492	0.629	0.286	0.128

	Bq/g soil	counts per sec	CR coconut cream	CR dilute coconut cream	CR ni	
Bq/g soil	1					
counts per sec	1	1				
CR coconut cream	0.066	0.066	1			
CR dilute cream	-0.038	-0.038	-0.095	1		
CR ni	0.167	0.167	0.134	-0.004	1	
CR iu	0.07	0.07	0.095	-0.083	0.021	
CR waini	0.035	0.035	0.002	0.024	-0.056	
CR mede	-0.047	-0.047	0.042	0.096	0.179	
CR jekeru	-0.038	-0.038	0.083	0.071	0.053	
CR pandanus raw	0.046	0.046	0.025	0.086	0.049	
CR pandanus cooked	-0.006	-0.006	0.04	-0.084	0.074	
CR papaya	0.077	0.077	-0.063	0.049	0.03	
CR breadfruit	0.154	0.154	-0.016	0.124	-0.061	
BMR female	0.086	0.086	0.055	-0.132	-0.03	
EI female	0.128	0.128	0.038	-0.032	-0.024	

Table A5.3 Pearson product moment correlations of model parameters determined from Monte Carlo simulations (con't.)

	CR iu	CR waini	CR mede	CR jekeru	CR pandanus raw	
CR iu	1					
CR waini	0.15	1				
CR mede	0.004	0.009	1			
CR jekeru	-0.042	0.005	0.103	1		
CR pandanus raw	0.001	0.081	0.077	0.229	1	
CR pandanus cooked	0.09	0.054	0.021	0.046	-0.006	
CR papaya	0.064	0.003	0.031	0.021	0.04	
CR breadfruit	-0.019	0.144	0.036	0.008	0.087	
BMR female	-0.045	-0.034	0.011	0.156	0.015	
EI female	0.048	0.002	-0.042	0.194	-0.008	

	CR pandanus cooked	CR papaya	CR breadfruit	BMR female	EI female	
CR pandanus cooked	1					
CR papaya	0.118	1				
CR breadfruit	-0.044	-0.165	1			
BMR female	0.048	-0.161	-0.062	1		
EI female	0.093	-0.034	-0.07	0.629	1	

A more sophisticated analysis of model sensitivity was obtained by calculations of standardized partial regression correlation coefficients (SPRC, see IAEA 1988). The SPRC is a measure of the number of standard deviations the predicted quantity (internal dose) will change if any of the input parameters (e.g., the CR values) are changed by one standard deviation, all other parameters in the expression remaining constant.

The SPRC values were determined by fitting a "response surface" (see Myers 1976) to the predictions of Internal Dose. A "fitted response surface" is a simplified mathematical expression obtained by linear regression of the simulated model predictions from the suite of simulated parameters. If the predictions parameters are first standardized, the resulting regression coefficients are the SPRC values.

This analysis indicated that Internal Dose could be predicted well ($R^2 = 0.80$) from only two parameters: the in-situ count rate and the individual energy intake (EI, kcal/y). This finding is in agreement with our intuitive notions of the the sources of internal dose. The predictions of Internal Dose can be substantially improved ($R^2 = 0.92$) with the addition of only three parameters: CR

values for jekeru, coconut cream, and pandanus. Only a minor addition to prediction accuracy is accomplished by adding another four parameters (see Table A5.4 below).

In summary, 92% of the variation in predicted internal doses can be explained by the variation in five parameters: ^{137}Cs count-rate, individual energy intake-rates, and the CR values for three important food products.

Table A5.4 Findings of the sensitivity analysis: Standardized partial regression correlation coefficients (SPRC).

Parameter	SPRC 2 parameter model	SPRC 5 parameter model	SPRC 9 parameter model
in-situ c/s (^{137}Cs)	0.739	0.733	0.718
energy-intake(kcal/y)	0.414	0.369	0.346
CR jekeru		0.206	0.198
CR coconut cream		0.186	0.185
CR pandanus (raw)		0.157	0.149
dose factor (Sv per Bq)			0.106
CR pandanus (cooked)			0.08
CR breadfruit			0.059
CR drinking ni			0.054
multiple R^2	0.80	0.92	0.94

CONCLUSIONS

The results of the dose modeling indicates that under the set of assumptions as stated in this chapter, the prescribed diets, except for the Mejatto diet, predict that significant proportions of the community would exceed the agreed upon compliance limit of 100 mrem/y. Only the Mejatto diet which incorporates, on average, about 18% local food does not exceed the limit.

Diet 3 which includes only local food and rice (about a 35% contribution) describes a diet of a relatively traditional lifestyle. The modeling indicates that between 35% and 45% of the population (men and women, respectively) might exceed the compliance limit with this diet.

Mitigative actions are possible to reduce the committed dose from ^{137}Cs . In particular, the use of potassium fertilizer would suppress the uptake of ^{137}Cs into coconuts (Robison and Stone 1992) and presumably other food crops as well. The potassium treatment of the soil constitutes the main recommendation of the Scientific Management Team and is discussed in more detail elsewhere in this report.

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Figure 1. Predictions of Internal Dose Equivalent as a
 Function of In-Situ Count-Rate
 Results of Monte Carlo Simulations (Diet 1, Adult Men)

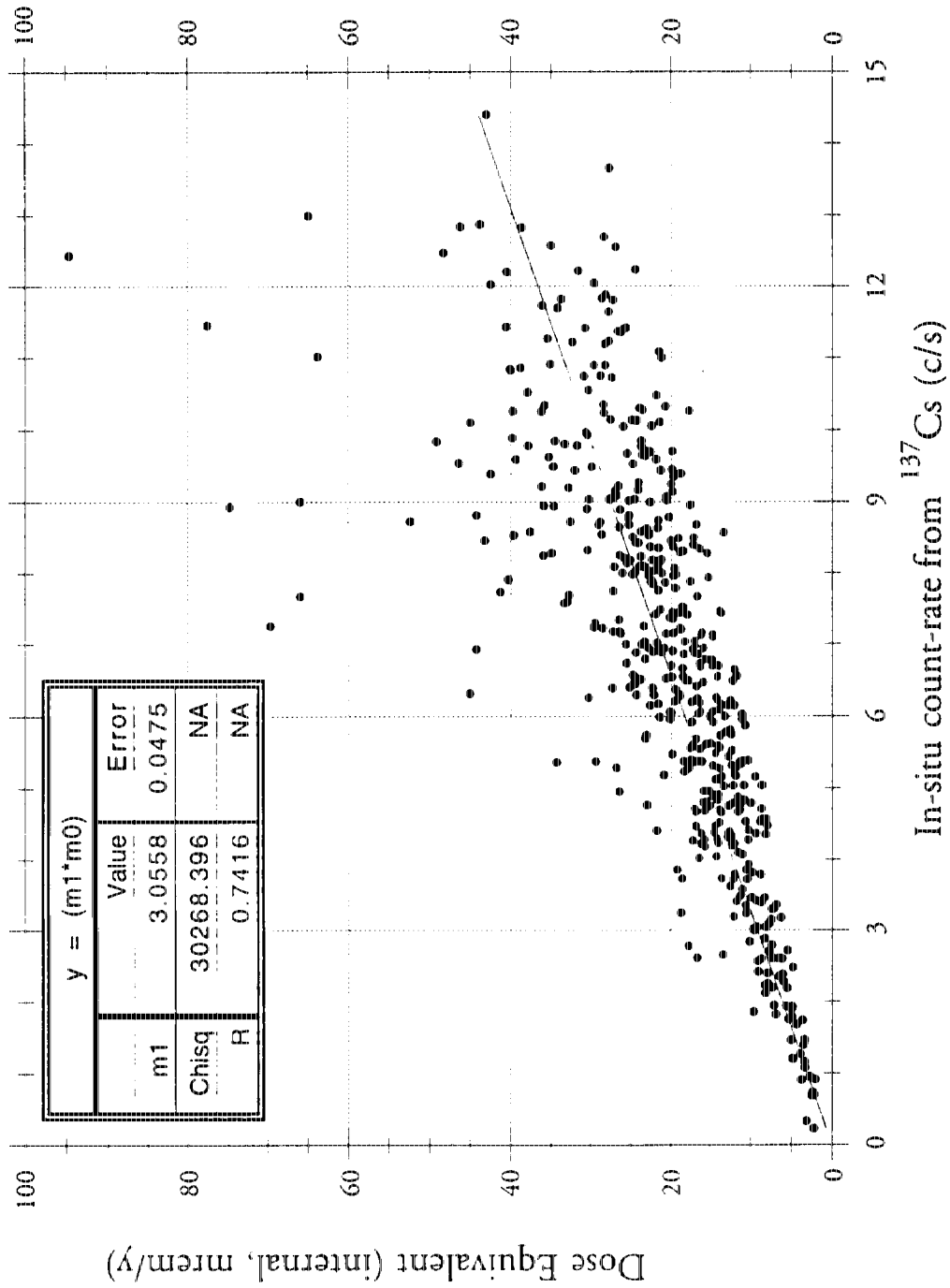


Figure 2. Results of Monte Carlo Simulations (n=1000)
Comparison of External, Internal and Total Dose for Adult Women

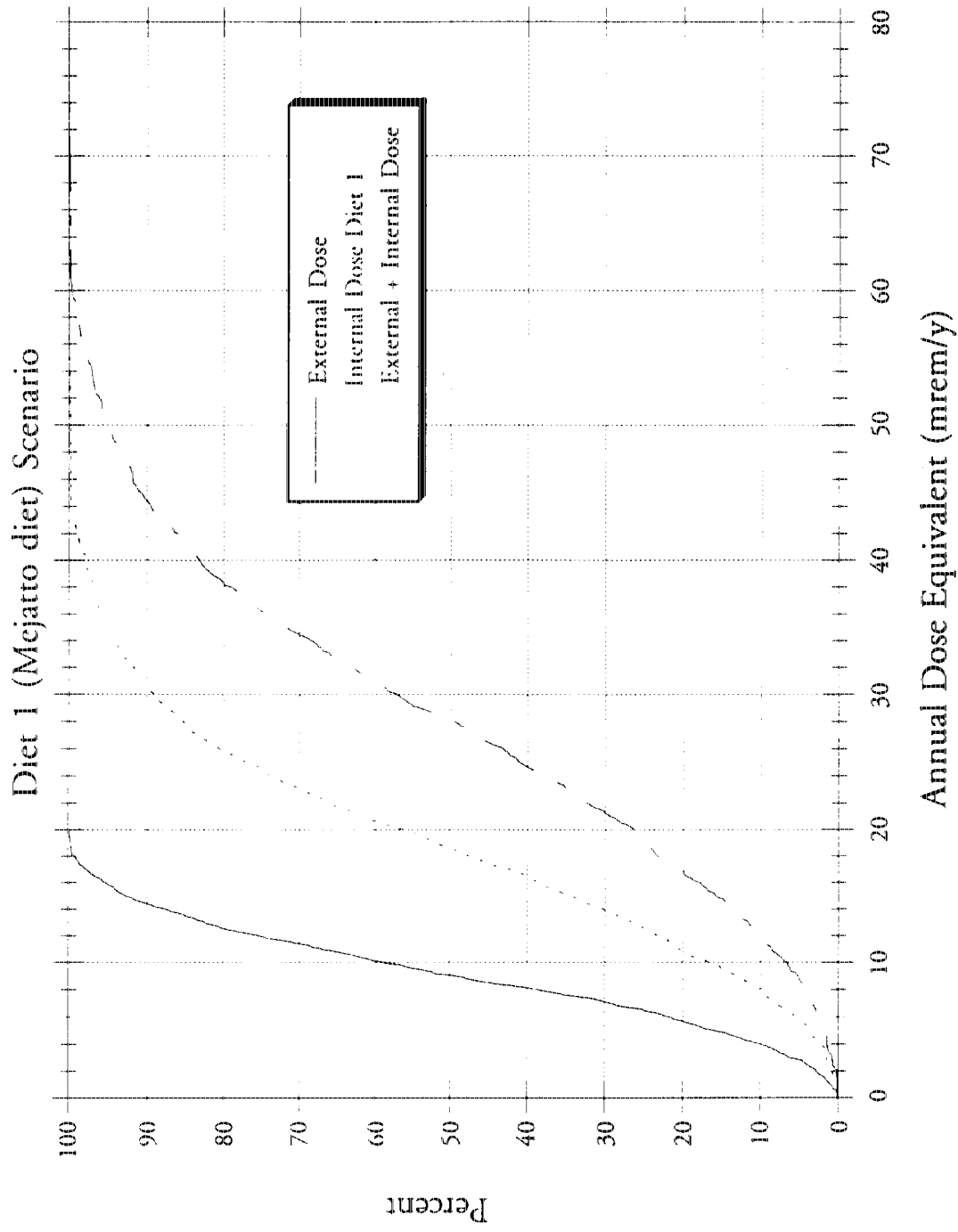


Figure 3. Results of Monte Carlo Simulations (n=1000)
 Comparison of External, Internal and Total Dose for Adult Men
 Diet 1 (Mejatto diet) Scenario

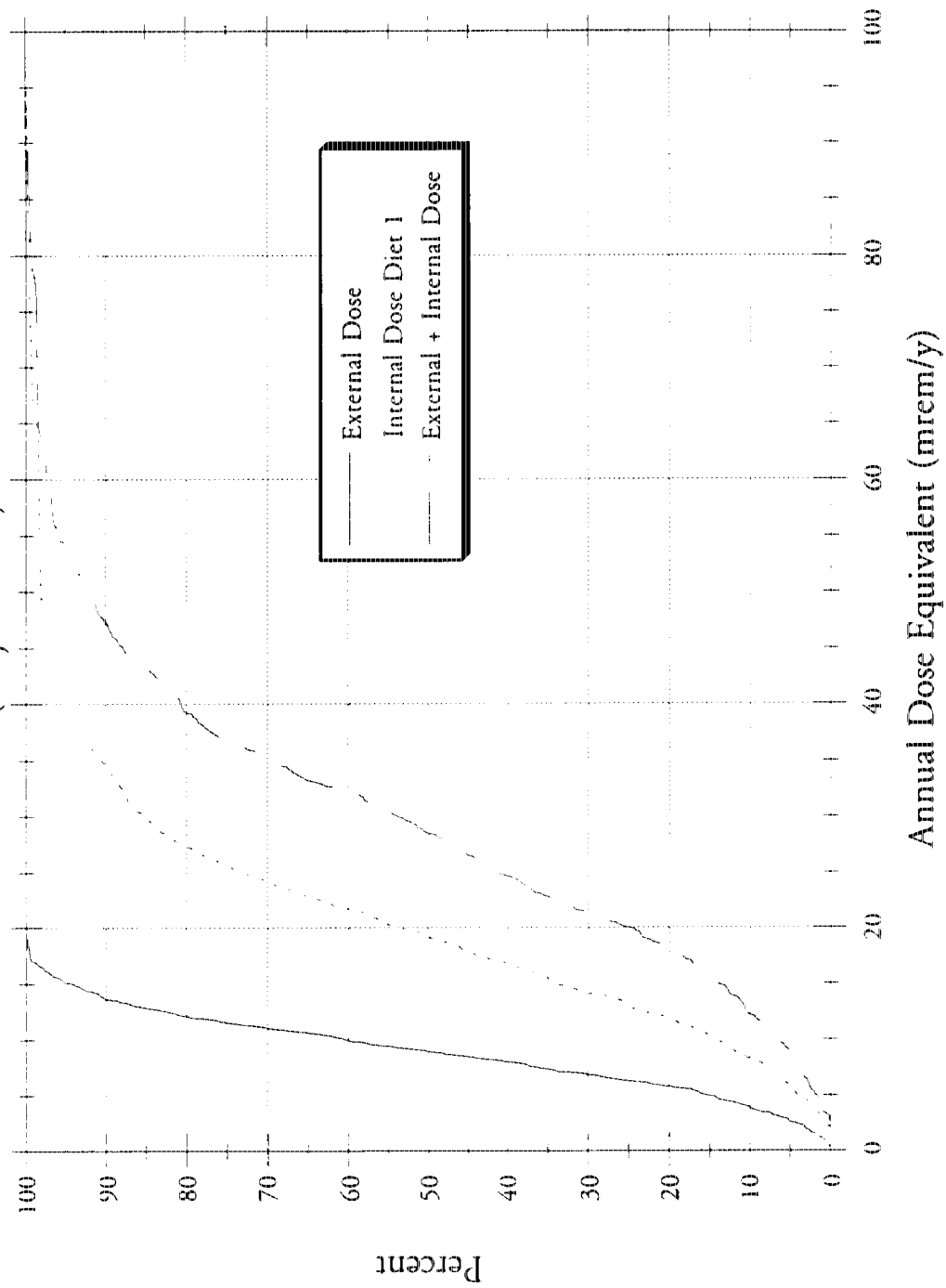


Figure 4. Results of Monte Carlo Simulations (n=1000)
Dose Assessment Model for Adult Women on Rongelap Island

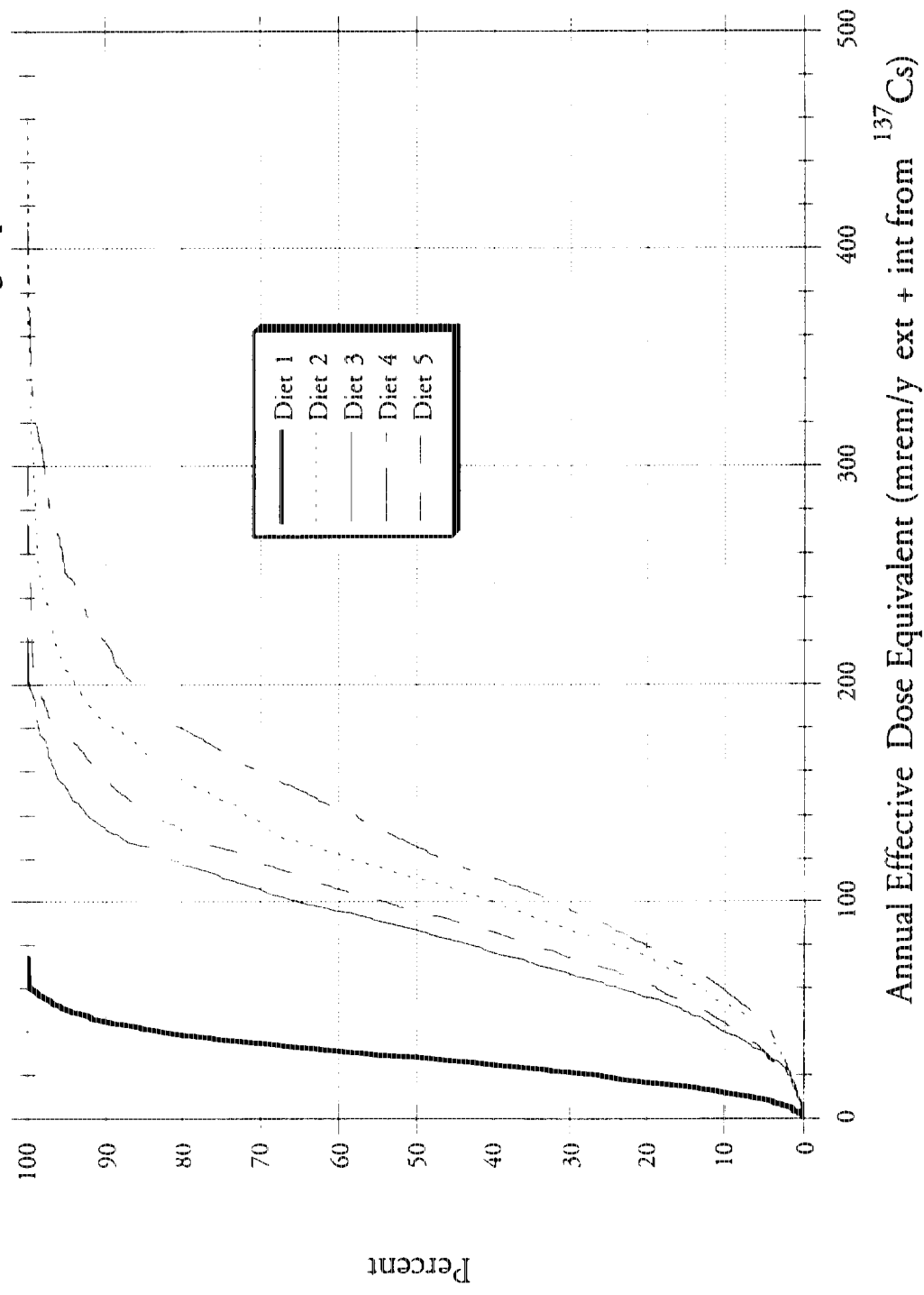
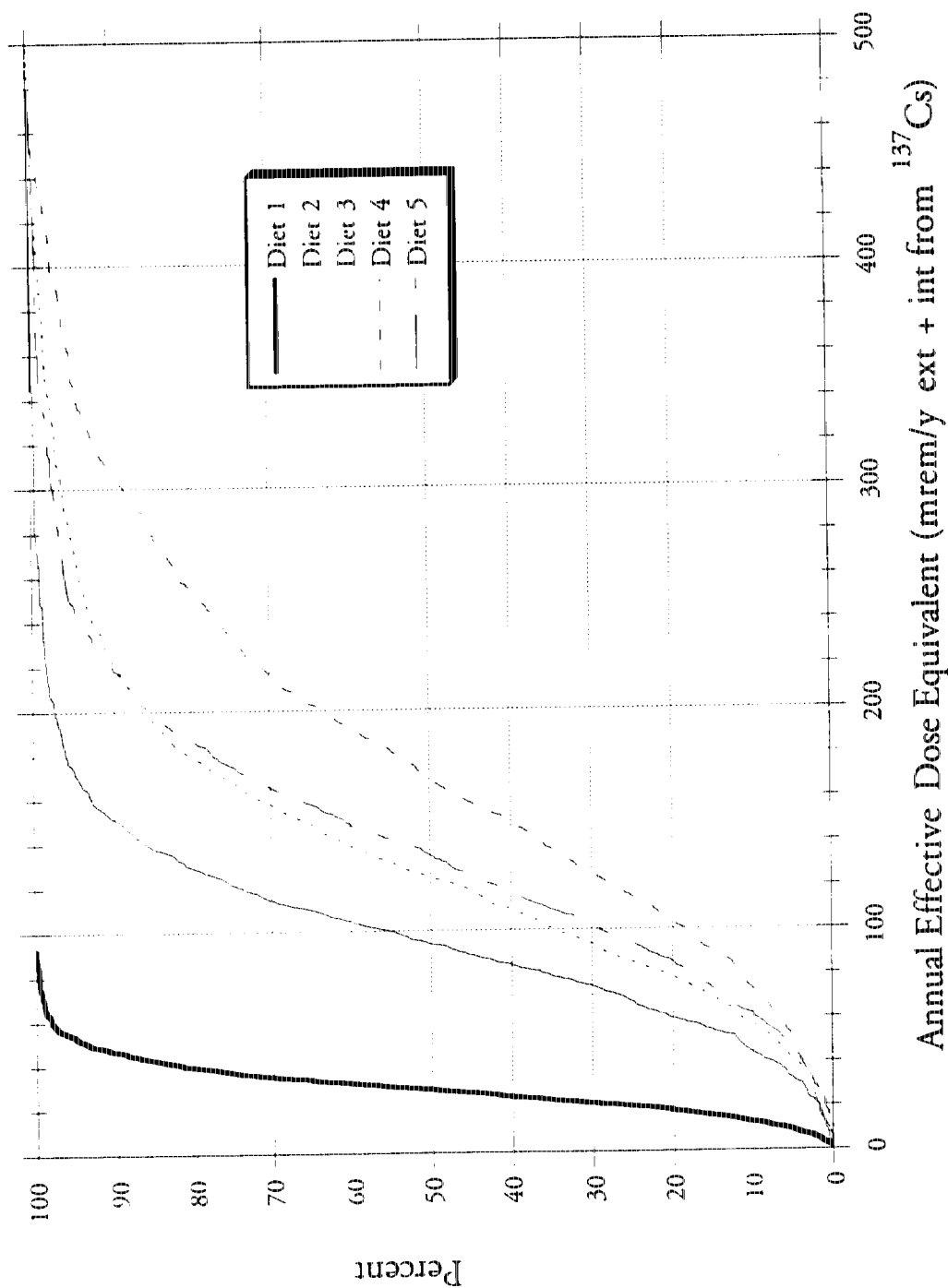


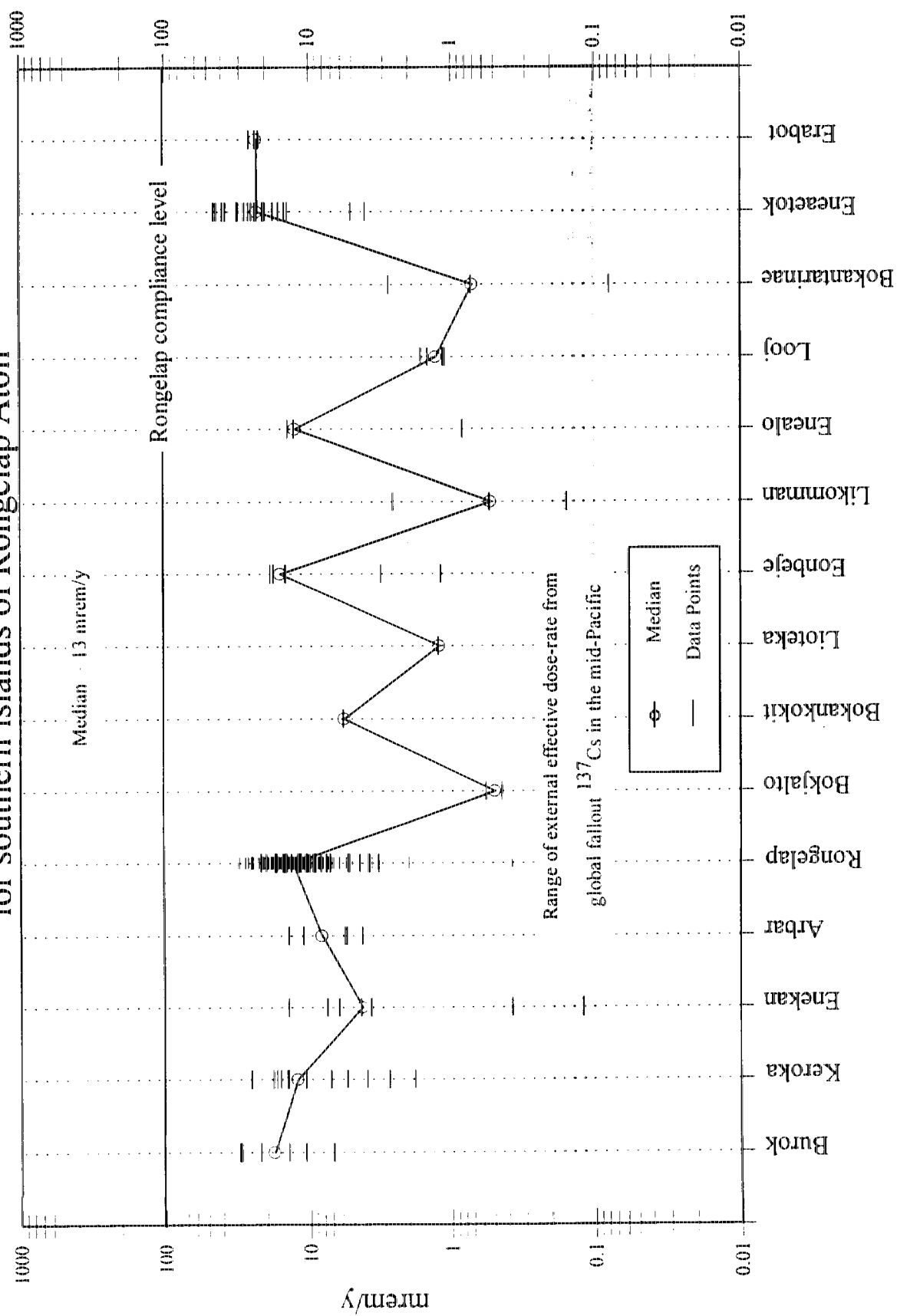
Figure 5. Results of Monte Carlo Simulations (n=1000)
Dose Assessment Model for Adult Men on Rongelap Island



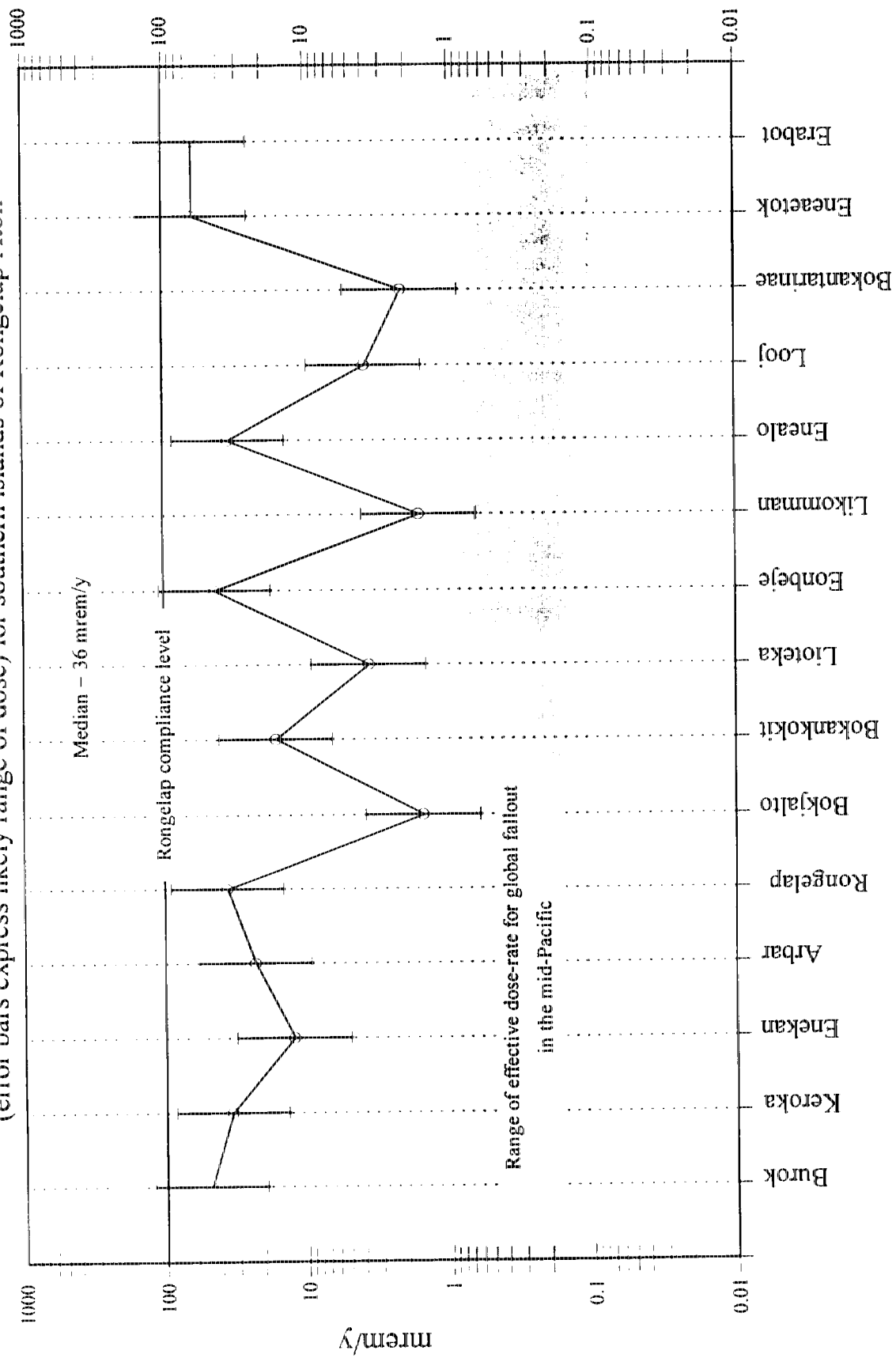
Summary Graphs of Predicted Dose (mrem/y) by Island In Southern Rongelap Atoll

- (i) external dose
- (ii) external plus internal dose (18% local food diet)
- (iii) external plus internal dose (75% local food diet)

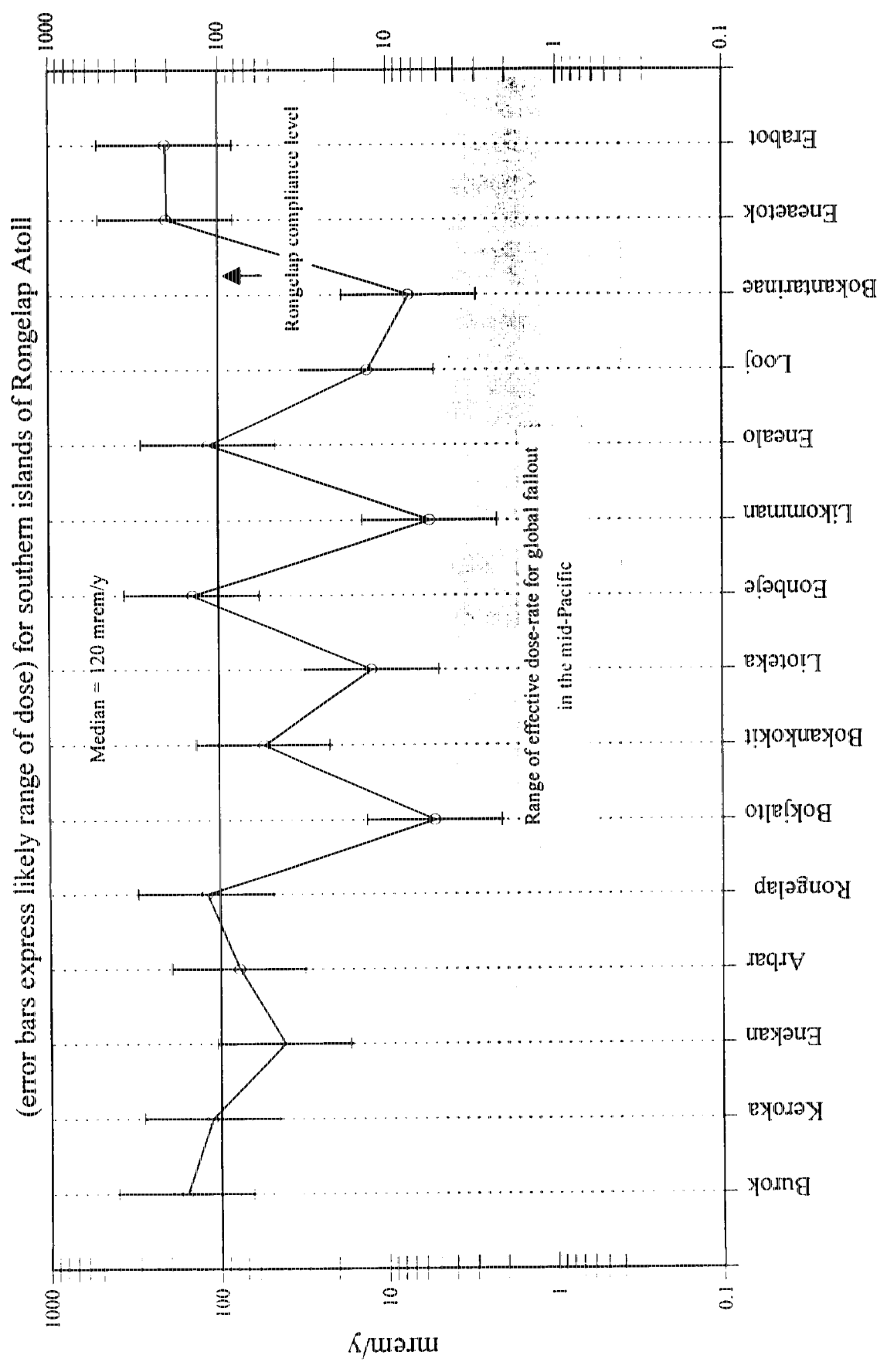
External effective dose-rate from ^{137}Cs (mrem/y) for southern islands of Rongelap Atoll



External plus internal effective dose-rate from ^{137}Cs (mrem/y)
 for a diet consisting of 18% local food with the remainder imported
 (error bars express likely range of dose) for southern islands of Rongelap Atoll



External plus internal effective dose-rate from ^{137}Cs (mrem/y)
for a diet of 75% local food and 25% rice
(error bars express likely range of dose) for southern islands of Rongelap Atoll



**An Analysis of Radiation Doses
That Could be Received Subsequent
to the Resettlement of Rongelap**

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1. INTRODUCTION

This note provides draft sections for the summary report on the Rongelap Resettlement Project. It comprises:

- a) A summary of the base case and sensitivity studies carried out in relation to external, internal and total doses from ^{137}Cs ;
- b) A comment on doses to children relative to those to adults from ^{137}Cs ;
- c) A comment on doses from other radionuclides.

2. DOSES FROM ^{137}Cs

Dose estimates were made using the computer code RONGDOS. This implements the radiological protection protocol accepted for this study and is documented elsewhere [1]. The input data required to utilise the code are detailed below, together with the values adopted and their justification. For convenience, the data are separated into four files relating to:

- a) the spatial distribution of ^{137}Cs count rates over the island;
- b) case-specific data comprising;
 - count rate to soil concentration conversion factor;
 - number of food types;
 - soil:plant concentration ratios for each food type;
 - energy contents for each food type;
 - fraction of time spent in residential areas;
 - exposure rate in residential areas;
 - conversion factors from count rate to exposure rate;
- c) dietary composition data, comprising the fraction of each food by mass in the overall diet;
- d) population data, comprising m and s values for log-normal distributions characterising the body mass and energy intake of the population.

In addition, the code includes hard-wired data on the relationship between exposure and the whole body dose for ^{137}Cs and on the relationships between intake and effective dose equivalent for ^{137}Cs , in each case as a function of body mass.

2.1 SPATIAL DISTRIBUTION OF ^{137}Cs COUNT RATES

These count rates were taken from the maps of $S(x)$ and $T_R(x)$ produced by the Mathematics Department, Lancaster University, in a digitised form on a 50m x 50m grid covering the whole island [2]. In the analyses presented here, $S(x)$ and $T_{500}(x)$ were used to represent spatial averaging over an area $\leq 100\text{m}$ in radius and $\sim 500\text{m}$ in radius, respectively.

2.2 CASE-SPECIFIC DATA

The count rate to soil concentration conversion factor was derived from data relating to locations where the twelve soil cores were taken. At each of these locations, the total areal concentration of ^{137}Cs was established, together with the associated count rate [3]. These data are summarised below.

Areal Concentration (Bq m^{-2})	Count Rate (c s^{-1})	Ratio (Bq m^{-2} per c s^{-1})
$1.20 \cdot 10^4$	3.30	3636
$1.82 \cdot 10^4$	6.63	2745
$3.45 \cdot 10^4$	10.95	3151
$2.60 \cdot 10^4$	8.14	3194
$1.18 \cdot 10^4$	7.26	1625
$2.26 \cdot 10^4$	6.26	3610
$2.66 \cdot 10^4$	16.68	1595
$1.62 \cdot 10^4$	8.43	1922
$3.07 \cdot 10^4$	10.87	2824
$1.63 \cdot 10^4$	4.97	3280
$1.38 \cdot 10^4$	9.19	1502
$1.01 \cdot 10^4$	4.91	2057

The mean ratio is 2595 and the standard error on the mean is 234. As Simon [3] provides an areal to mass concentration conversion factor of $35 \text{ Bq m}^{-2} \equiv 1 \text{ Bq kg}^{-1}$, the appropriate count rate to soil conversion factor is $74.1 \pm 6.7 \text{ Bq kg}^{-1}$ per c s^{-1} . A value of 74.1 is used in the base-case studies reported herein.

The number of food types has been given as 38 by Franke [4]. However, these are local foods only. Thus, a 39th food has been added to provide the energy fraction of the diet not supplied by local foods. This 39th food is taken to have the energy content of rice ($1130 \text{ kcal kg}^{-1}$).

The soil:plant concentration ratios for the various food types were based on data for coconut juice and coconut meat provided by Simon [5].

The geometric mean value for coconut juice relative to soil is 0.13, whereas the geometric mean value for coconut meat (dry basis) relative to soil is 1.02. However, the geometric mean wet:dry ratio for drinking coconut meat is 5.3, so the corresponding soil:plant concentration ratio for drinking coconut meat (wet basis) is 0.19. The 1% and 99% values are about one order of magnitude above and below the mean in each case, but the 25% and 75% values are about a factor of two below and above the mean, respectively. Because many food items will be eaten in a year, it is not appropriate to utilise the full range of the distribution in sensitivity studies. Thus a factor of 0.2 is adopted in the base case for all foodstuffs and a range of 0.1 to 0.4 is considered in sensitivity studies. For aquatic foodstuffs, a concentration ratio of zero is adopted, to ensure that their ^{137}Cs content is properly set to zero. The food types considered, their energy contents and the associated concentration ratios are listed in Table 1.

The fraction of time spent in residential areas is based on previous DoE assumptions [6]:

- 9 h d⁻¹ spent in the house, with an exposure rate of 0.93 $\mu\text{R h}^{-1}$;
- 6 h d⁻¹ around the house and in the village area, with an exposure rate of 2.2 $\mu\text{R h}^{-1}$;
- 2 h d⁻¹ on the beach or lagoon, with an exposure rate of 0.1 $\mu\text{R h}^{-1}$.

Thus, the fraction of time spent in the island interior is 0.29 (7 h d⁻¹). The residual fraction of 0.71 is attributed to residential areas, at an average exposure rate of $(0.93 \times 9 + 2.2 \times 6 + 0.1 \times 2)/17 = 1.28 \mu\text{R h}^{-1}$ or 11.2 mR y⁻¹.

For evaluation of dose rates in the island interior, Simon [3], has proposed a single average conversion factor of $0.249 (\alpha/\rho)^{-0.122} \mu\text{R h}^{-1}$ per c s⁻¹. For his recommended average α/ρ value of 0.20 cm² g⁻¹, this corresponds to 2.656 mR y⁻¹ per c s⁻¹.

2.3 DIETARY COMPOSITION DATA

Franke [4] has defined five diets to be considered. These are described below.

Diet	Description
1	The current level of local food items as observed in the Mejatto survey.
2	Imported food items in diet 1 are replaced by local food items on a calorie-by-calorie basis in the same proportions as these local food items were consumed in the average on Mejatto during the survey.
3	As diet 2, but including the average rice consumption observed on Mejatto.
4	Imported food items in diet 1 are replaced by local food items on a calorie-by-calorie basis in the same average proportions as these local food items were reported by Naidu et al. [7]
5	As diet 4, but including the average rice consumption as observed on Mejatto.

Franke [4] provides dietary compositions in energy terms separately for men and women. In each case, the individuals are > 18 years of age. Using the energy contents of the foods, these values have been converted to fractional compositions by mass. Results are given in Table 2.

2.4 POPULATION DATA

The body mass and Energy Intake/Basal Metabolic Rate (EI/BMR) of the population are both fitted by log-normal distributions:

$$P(x) = \frac{1}{(2\pi)^{1/2} s x} \exp \left[-\frac{(\ln x - m)^2}{2s^2} \right]$$

Values of m and s for body mass (kg) have been provided by Franke [8] and are listed below.

		Males	Females
Body mass	m	4.223	4.136
	s	0.170	0.183

Similarly, values of m and s for the ratio EI/BMR have also been provided by Franke [4].

		Males	Females
EI/BMR	m	0.45	0.33
	s	0.19	0.14

In calculating the actual energy intake rate, r , use is made of the linear relationships:

$$\text{BMR} = \alpha + \beta \cdot W$$

where W is the body mass and α and β are constant coefficients.

Values of α and β have been obtained from Warwick [9], converting from MJ d⁻¹ to kcal d⁻¹ and using values appropriate to persons of age 18 to 30. These values are listed below.

	Males	Females
α (kcal d ⁻¹)	691.8	486.4
β (kcal d ⁻¹ kg ⁻¹)	15.05	14.81

2.5 DOSIMETRIC FACTORS

For an adult anthropomorphic phantom, exposure to whole-body dose conversion factors can be taken from Table 3a of ICRP Publication 51 [10]. At 0.6 MeV, the value for a rotationally symmetric field is 0.719 rem R⁻¹ and for isotropic field it is 0.609 rem R⁻¹. For smaller-sized phantoms the value increases, tending to a value ~1.0 rem R⁻¹ if differences in the stopping power of air and tissue are neglected. Here, a value of 0.7 rem R⁻¹ is adopted for a body mass of 70 kg and a value of 1.0 for a body mass of 4.2 kg. Values at other masses are obtained by linear interpolation or are set to the appropriate limiting values (0.7 or 1.0) above and below the mass range of 4.2 to 70 kg.

Values of dose per unit intake are taken directly from ICRP Publication 56 [11], as listed below.

Body Mass (kg)	Dose per Unit Intake (Sv Bq ⁻¹)
6.0	2.0 10 ⁻⁸
9.8	1.1 10 ⁻⁸
19.0	9.0 10 ⁻⁹
32.0	9.8 10 ⁻⁹
55.0	1.4 10 ⁻⁸
70.0	1.3 10 ⁻⁸

Values at intermediate masses are obtained by linear interpolation. Beyond this mass range, the limiting values are adopted.

2.6 RESULTS

Results for the base case, using $S(x)$, are illustrated in Figures 1 to 6. For both males and females, external doses exhibit narrow distributions with 50th percentiles at 9.5 mrem in each case (Figs 1 and 4). In contrast, both internal dose (Figs 2 and 5) and total dose (Figs 3 and 6) exhibit very broad distributions, which differ substantially between the different diets. It is convenient to summarise the results in terms of the doses associated with specific percentiles of the distributions and this is done below.

Males					
Percentile	Total Dose (mrem)				
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	16.5	49.5	37.5	82.5	60.5
5	17.5	59.5	44.5	100.5	73.5
10	18.5	64.5	48.5	110.5	80.5
25	20.5	72.5	54.5	125.5	91.5
50	22.5	85.5	63.5	148.5	107.5
75	25.5	101.5	74.5	177.5	128.5
90	28.5	118.5	87.5	209.5	151.5
95	30.5	130.5	95.5	230.5	165.5
99	34.5	152.5	110.5	271.5	194.5

Females					
Percentile	Total Dose (mrem)				
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	16.5	46.5	37.5	65.5	51.5
5	17.5	54.5	43.5	76.5	60.5
10	18.5	59.5	47.5	84.5	66.5
25	20.5	67.5	53.5	95.5	74.5
50	22.5	78.5	61.5	111.5	86.5
75	25.5	91.5	71.5	131.5	102.5
90	27.5	105.5	82.5	152.5	117.5
95	29.5	114.5	88.5	165.5	127.5
99	32.5	130.5	100.5	188.5	145.5

When $T_{500}(x)$ is used as a basis, these distributions are narrowed, as would be expected. Thus, for example, for Males (Diet 2), the 5% value is increased to 65.5 mrem and the 95% value is reduced to 124.5 mrem. However, these are not substantial differences.

Also, it will be noted that external exposure is a minor contributor to dose from ^{137}Cs (typically ~12% for Diet 2). Thus, the key uncertainty is identified as being the soil:plant concentration ratios adopted, since the dietary compositions are fixed and the energy intake and body mass distributions have been characterised and justified in detail. Setting the soil:plant concentration ratio at 0.4 (i.e. the 75% value of the observed distribution) yields the following results for Males, using $S(x)$ as a basis.

Percentile	Total Dose (mrem)				
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	22.5	88.5	65.5	155.5	112.5
5	26.5	108.5	79.5	192.5	138.5
10	27.5	119.5	87.5	210.5	151.5
25	30.5	135.5	98.5	241.5	173.5
50	35.5	160.5	116.5	286.5	204.5
75	41.5	192.5	139.5	344.5	246.5
90	47.5	227.5	164.5	410.5	291.5
95	51.5	250.5	180.5	452.5	321.5
99	58.5	294.5	212.5	533.5	379.5

Conversely, reducing the soil:plant concentration ratio to its 25% value of 0.1, yields the following results for Males, with $S(x)$ as a basis.

Percentile	Total Dose (mrem)				
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	12.5	29.5	23.5	45.5	35.5
5	13.5	34.5	26.5	55.5	41.5
10	13.5	36.5	28.5	59.5	44.5
25	14.5	41.5	31.5	67.5	50.5
50	16.5	47.5	36.5	79.5	58.5
75	17.5	55.5	42.5	93.5	69.5
90	19.5	64.5	48.5	110.5	80.5
95	20.5	70.5	53.5	120.5	88.5
99	22.5	81.5	60.5	141.5	102.5

3. DOSES TO CHILDREN FROM ^{137}Cs

As demonstrated in Section 2.5, the dose per unit intake increases only slowly as body mass decreases, mainly because of the shorter half life for caesium retention in children. In practice, the energy intake rate (and hence food intake rate) of small children is substantially less than that of adults. This is demonstrated by the following table, which is based on the detailed results of dietary survey described elsewhere [4].

Body Mass (kg)	Mean EI (kcal d ⁻¹)	
	Males	Females
6-10	988	1016
11-15	2083	1746
16-20	1986	1370
21-25	2141	1801
26-30	2199	1801
Adults	2750	1900

Thus, at a body mass of 6-10 kg, the energy intake is ~0.36 (Males) or 0.53 (Females) of the adult value, whereas the dose per unit intake value is a factor 1.5 (Males) or 1.4 (Females) larger than the adult value. Thus, combining these factors, ^{137}Cs doses to small children are typically 54% (Males) or 74% (Females) of the adult values.

4. CONTRIBUTIONS FROM OTHER RADIONUCLIDES

As Simon [3] has shown, ^{137}Cs provides about 99% of the total external exposure, with ^{241}Am and ^{60}Co being the other contributing radionuclides. As external exposure is a minor contributor to total dose (Section 2.6) this matter does not require further consideration.

With respect to internal exposure, assays of skeletal tissue from deceased individuals who lived on Rongelap over the period 1957 to 1985 have shown that internal doses from isotopes of plutonium and americium will be no more than a small fraction of 1 mrem y⁻¹ [12].

However, Rongelap remains contaminated with ⁹⁰Sr, which has not been studied in the context of the Rongelap Resettlement Project.

Data from the Lawrence Livermore National Laboratory [13] demonstrate that ⁹⁰Sr concentrations in major terrestrial foodstuffs are about two orders of magnitude less than ¹³⁷Cs concentrations, while dose per unit intake values are about a factor of 2.7 larger [11]. Thus, overall, the contribution from ⁹⁰Sr is expected to increase internal doses by no more than ~3%.

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TABLE 1
Food Types, Energy Contents and Concentration Ratios

Food No.	Food Type	Energy Content (kcal kg ⁻¹)	Concentration Ratio
1	Bananas (raw, peeled)	920	0.2
2	Bird, wild, roasted	2100	0.2
3	Coconut cream (solid)	3500	0.2
4	Coconut milk	2500	0.2
5	Coconut, drinking, NI	110	0.2
6	Coconut Embryo, IU	830	0.2
7	Coconut, hard, WAINI	4100	0.2
8	Coconut, soft, MEDE	1100	0.2
9	Coconut Crab, blue, boiled	850	0.2
10	JEKERU, incl. JEKMAI	480	0.2
11	JEMANIN (fermented JEKERU)	510	0.2
12	Pandanus fruit, raw	640	0.2
13	Pandanus fruit, cooked	640	0.2
14	Papayas, raw	390	0.2
15	Pork	3000	0.2
16	Pumpkin	200	0.2
17	Reef fish (boiled, poached)	1100	0.0
18	Reef fish (grilled, bbq)	1300	0.0
19	Reef fish (pan fried, no flour)	1100	0.0
20	Salt fish	1100	0.0
21	Sashimi (Tuna, Trolling Fish)	1000	0.0
22	Tuna, Trolling Fish (cooked)	1200	0.0
23	Watermelon (raw)	320	0.2
24	Breadfruit, incl BWIRO	1000	0.2
25	Coconut, KENAWA	100	0.2
26	Arrowroot flour	3600	0.2
27	Sweet Potatoes	1100	0.2
28	Breadfruit Seeds, roasted	2100	0.2
29	Plantains, cooked	1200	0.2
30	Turtle	890	0.0
31	Lobster	1000	0.0
32	Clams, giant	1500	0.0
33	Snails	900	0.0
34	Octopus	1600	0.0
35	Clams, small	1500	0.0
36	Jankwon	2900	0.2
37	Chicken	2400	0.2
38	Local vegetables	350	0.2
39	Non-local food (≡ Rice)	1130	0.0

Food	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	0.000E+00	0.000E+00	0.000E+00	6.285E-03	4.787E-03
2	6.177E-03	4.601E-02	2.978E-02	1.741E-03	1.311E-03
3	2.729E-02	2.050E-01	1.321E-01	0.000E+00	0.000E+00
4	7.075E-03	5.212E-02	3.426E-02	8.504E-03	6.239E-03
5	1.040E-02	7.852E-02	5.067E-02	3.170E-01	2.419E-01
6	6.393E-04	4.762E-03	3.112E-03	1.025E-01	7.738E-02
7	2.301E-03	1.714E-02	1.127E-02	5.393E-02	4.252E-02
8	2.144E-03	1.597E-02	1.075E-02	7.653E-02	5.838E-02
9	5.411E-04	4.134E-03	2.719E-03	3.802E-03	2.914E-03
10	3.685E-02	2.714E-01	1.756E-01	1.152E-01	8.792E-02
11	1.595E-03	1.206E-02	7.730E-03	0.000E+00	0.000E+00
12	5.528E-03	4.117E-02	2.761E-02	4.119E-02	3.154E-02
13	2.580E-03	1.967E-02	1.296E-02	0.000E+00	0.000E+00
14	2.933E-03	2.215E-02	1.464E-02	1.003E-02	7.763E-03
15	1.179E-03	8.784E-03	5.891E-03	7.086E-04	5.505E-04
16	6.486E-04	4.758E-03	3.127E-03	1.701E-03	1.284E-03
17	5.467E-03	4.126E-02	2.719E-02	7.499E-02	5.755E-02
18	5.624E-03	4.279E-02	2.719E-02	0.000E+00	0.000E+00
19	6.111E-03	4.658E-02	3.090E-02	0.000E+00	0.000E+00
20	6.861E-04	5.191E-03	3.337E-03	0.000E+00	0.000E+00
21	3.538E-03	2.635E-02	1.767E-02	0.000E+00	0.000E+00
22	4.520E-03	3.416E-02	2.266E-02	6.874E-02	5.275E-02
23	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
24	0.000E+00	0.000E+00	0.000E+00	7.058E-02	5.413E-02
25	0.000E+00	0.000E+00	0.000E+00	7.313E-03	5.596E-03
26	0.000E+00	0.000E+00	0.000E+00	1.606E-03	1.223E-03
27	0.000E+00	0.000E+00	0.000E+00	2.242E-04	1.668E-04
28	0.000E+00	0.000E+00	0.000E+00	1.255E-03	9.611E-04
29	0.000E+00	0.000E+00	0.000E+00	6.094E-03	4.587E-03
30	0.000E+00	0.000E+00	0.000E+00	6.306E-04	4.845E-04
31	0.000E+00	0.000E+00	0.000E+00	4.847E-04	3.670E-04
32	0.000E+00	0.000E+00	0.000E+00	6.236E-04	4.832E-04
33	0.000E+00	0.000E+00	0.000E+00	9.449E-03	7.238E-03
34	0.000E+00	0.000E+00	0.000E+00	7.972E-04	5.734E-04
35	0.000E+00	0.000E+00	0.000E+00	1.757E-03	1.346E-03
36	0.000E+00	0.000E+00	0.000E+00	9.970E-03	7.593E-03
37	0.000E+00	0.000E+00	0.000E+00	4.252E-04	3.211E-04
38	0.000E+00	0.000E+00	0.000E+00	6.074E-03	4.718E-03
39	8.662E-01	0.000E+00	3.489E-01	0.000E+00	2.355E-01

Table 2a
Fractional Dietary Composition by Mass (Males, >18 years)

Food	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
1	1.371E-03	8.304E-03	6.237E-03	6.285E-03	5.026E-03
2	9.825E-04	5.751E-03	4.302E-03	1.741E-03	1.382E-03
3	2.686E-02	1.584E-01	1.186E-01	0.000E+00	0.000E+00
4	4.585E-03	2.662E-02	2.002E-02	8.504E-03	6.891E-03
5	2.188E-02	1.344E-01	9.657E-02	3.170E-01	2.555E-01
6	3.038E-04	1.782E-03	1.353E-03	1.025E-01	8.193E-02
7	3.634E-03	2.134E-02	1.578E-02	5.393E-02	4.423E-02
8	2.293E-04	1.344E-03	9.990E-04	7.653E-02	6.182E-02
9	0.000E+00	0.000E+00	0.000E+00	3.802E-03	3.093E-03
10	3.104E-02	1.874E-01	1.399E-01	1.152E-01	9.256E-02
11	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
12	1.451E-02	8.472E-02	6.295E-02	4.119E-02	3.400E-02
13	5.985E-03	4.043E-02	3.052E-02	0.000E+00	0.000E+00
14	7.348E-03	4.424E-02	3.131E-02	1.003E-02	8.137E-03
15	1.299E-03	7.804E-03	5.698E-03	7.086E-04	5.742E-04
16	1.261E-03	7.394E-03	5.555E-03	1.701E-03	1.360E-03
17	6.044E-03	3.585E-02	2.664E-02	7.499E-02	6.017E-02
18	1.028E-03	1.232E-02	8.922E-03	0.000E+00	0.000E+00
19	1.667E-02	9.746E-02	7.215E-02	0.000E+00	0.000E+00
20	2.188E-03	1.232E-02	9.546E-03	0.000E+00	0.000E+00
21	3.439E-04	1.972E-03	1.465E-03	0.000E+00	0.000E+00
22	2.197E-03	1.335E-02	9.666E-03	6.874E-02	5.516E-02
23	2.687E-03	1.540E-02	1.145E-02	0.000E+00	0.000E+00
24	1.376E-02	8.133E-02	6.105E-02	7.058E-02	5.712E-02
25	0.000E+00	0.000E+00	0.000E+00	7.313E-03	5.894E-03
26	0.000E+00	0.000E+00	0.000E+00	1.606E-03	1.310E-03
27	0.000E+00	0.000E+00	0.000E+00	2.242E-04	1.813E-04
28	0.000E+00	0.000E+00	0.000E+00	1.255E-03	9.931E-04
29	0.000E+00	0.000E+00	0.000E+00	6.094E-03	4.911E-03
30	0.000E+00	0.000E+00	0.000E+00	6.306E-04	5.094E-04
31	0.000E+00	0.000E+00	0.000E+00	4.847E-04	3.899E-04
32	0.000E+00	0.000E+00	0.000E+00	6.236E-04	5.078E-04
33	0.000E+00	0.000E+00	0.000E+00	2.449E-03	7.657E-03
34	0.000E+00	0.000E+00	0.000E+00	7.972E-04	6.234E-04
35	0.000E+00	0.000E+00	0.000E+00	1.757E-03	1.451E-03
36	0.000E+00	0.000E+00	0.000E+00	9.970E-03	8.754E-03
37	0.000E+00	0.000E+00	0.000E+00	4.252E-04	3.400E-04
38	0.000E+00	0.000E+00	0.000E+00	6.074E-03	4.922E-03
39	3.318E-01	0.000E+00	2.593E-01	0.000E+00	1.926E-01

Table 2b
Fractional Dietary Composition by Mass (Females, > 18 years)

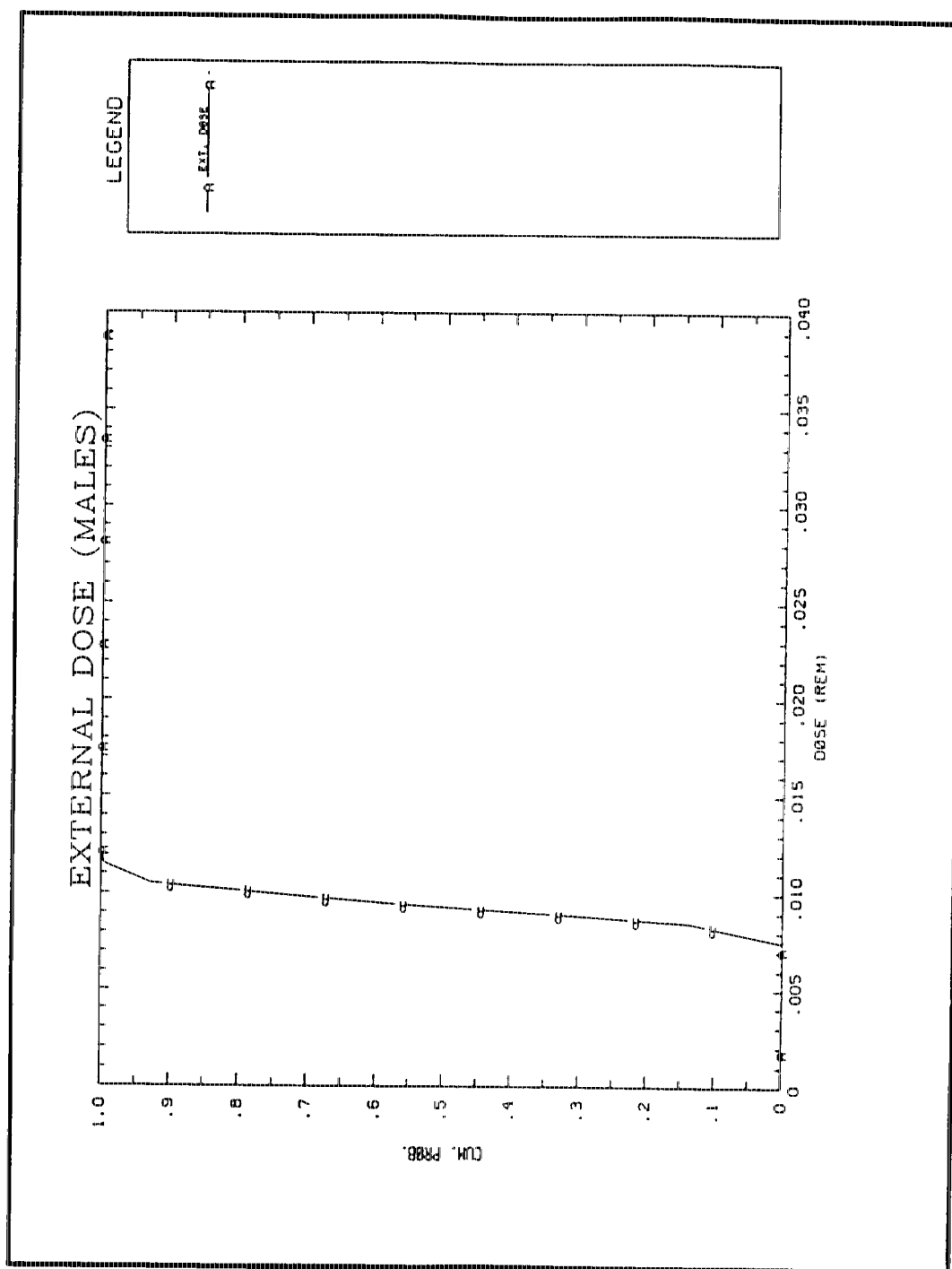


Figure 1
Males: Base Case: External Dose: Based on S(x)

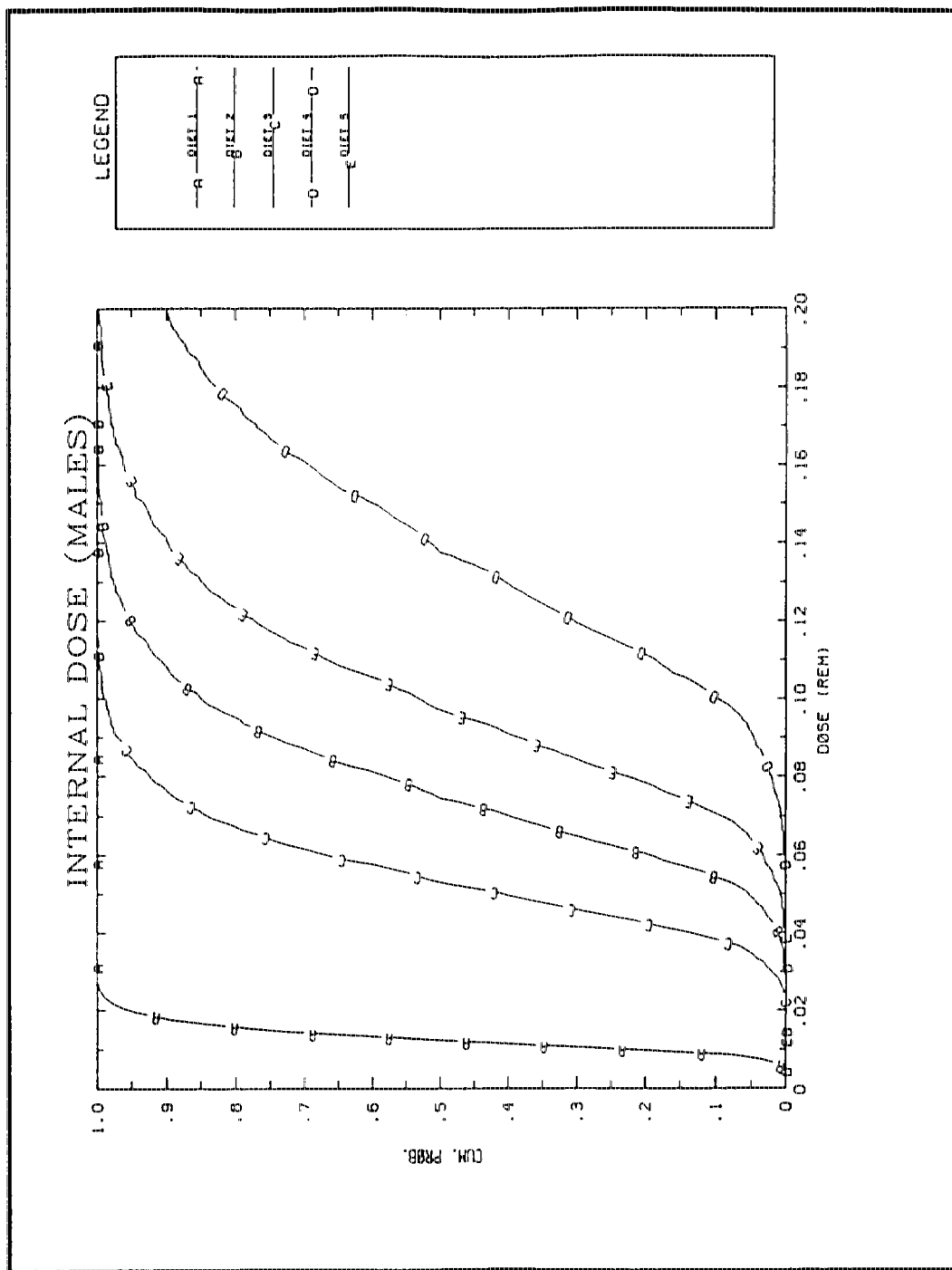


Figure 2
Males: Base Case: Internal Dose: Based on S(x)

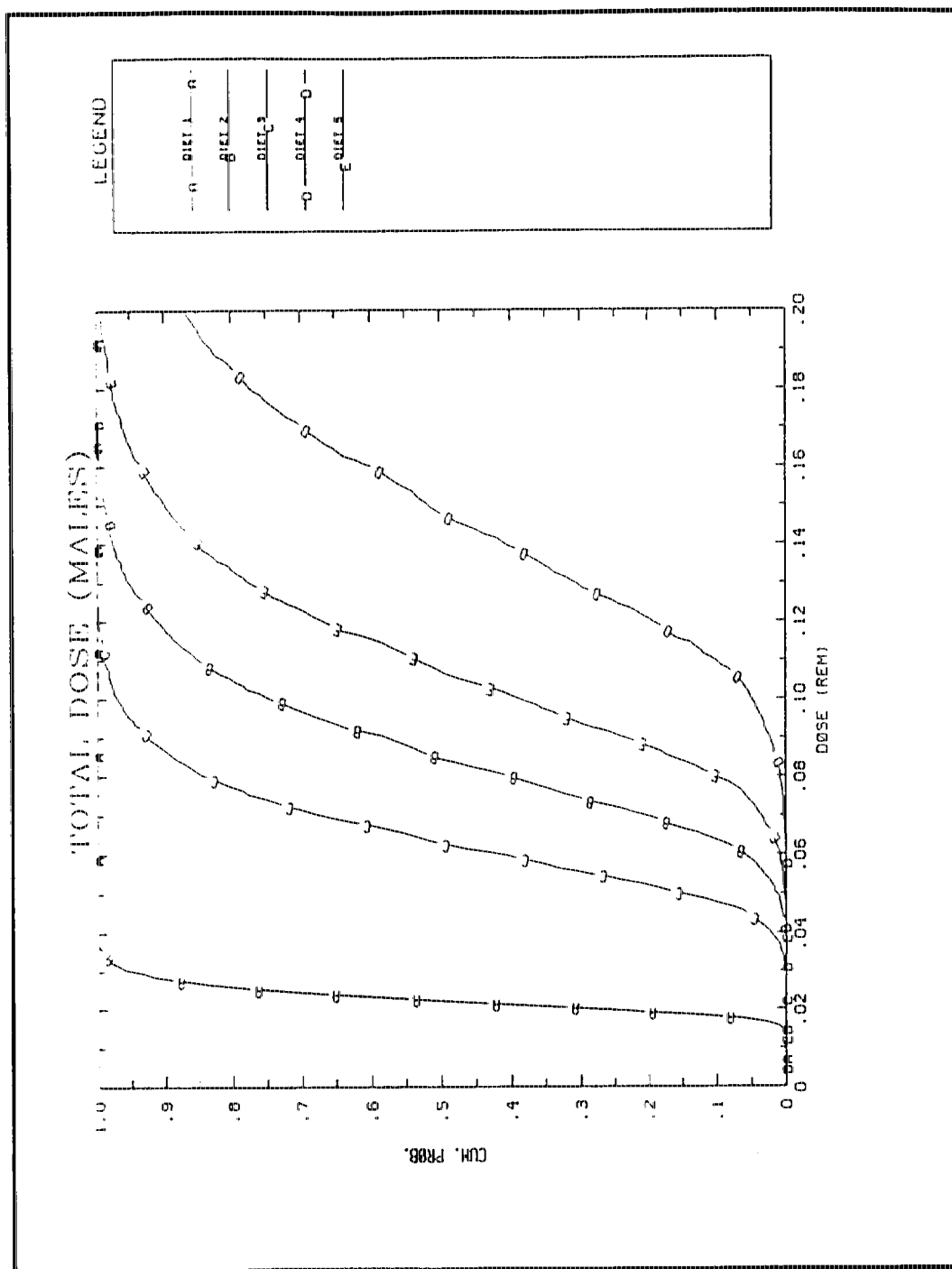


Figure 3
Males: Base Case: Total Dose: Based on $S(x)$

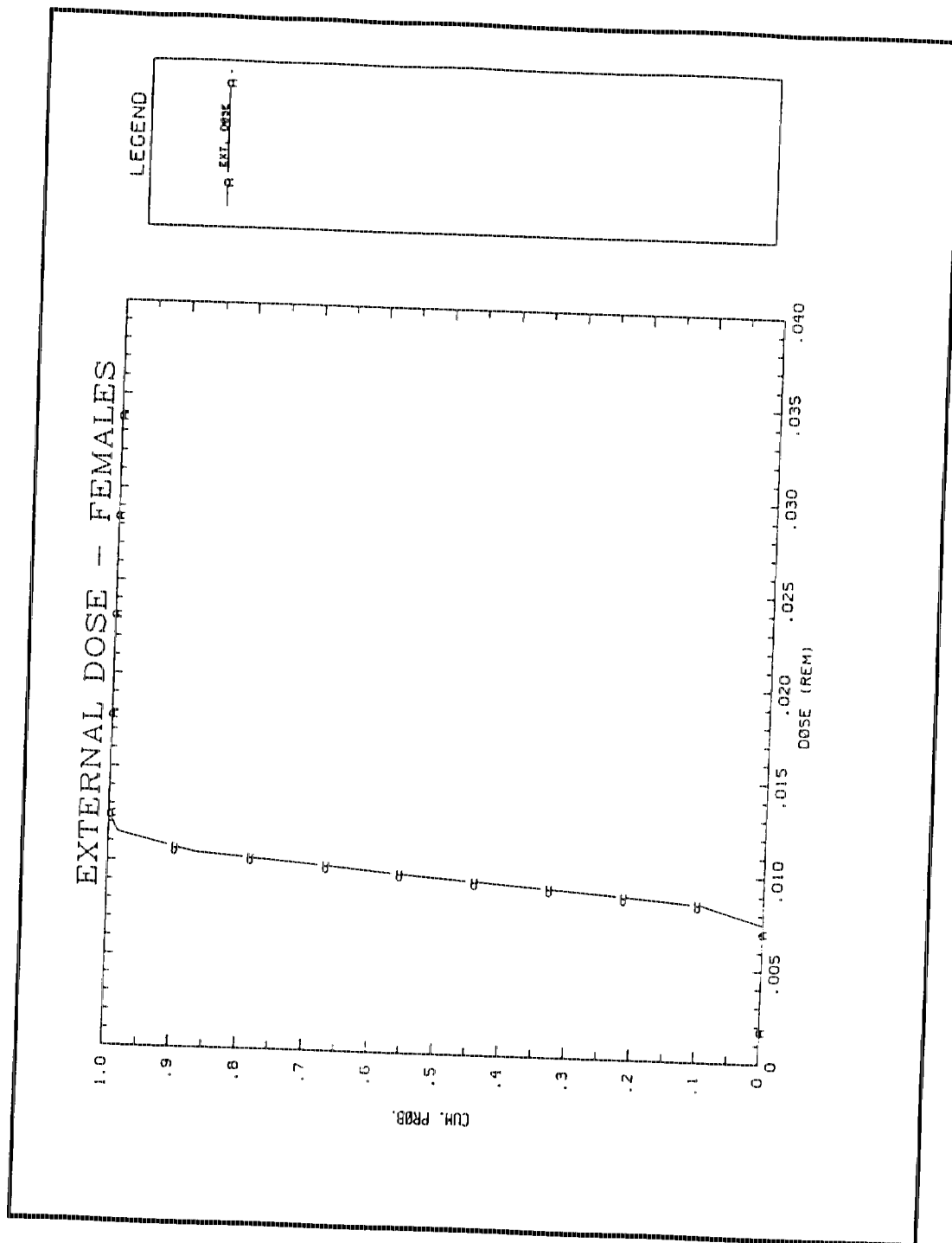


Figure 4
Females: Base Case: External Dose: Based on $S(x)$

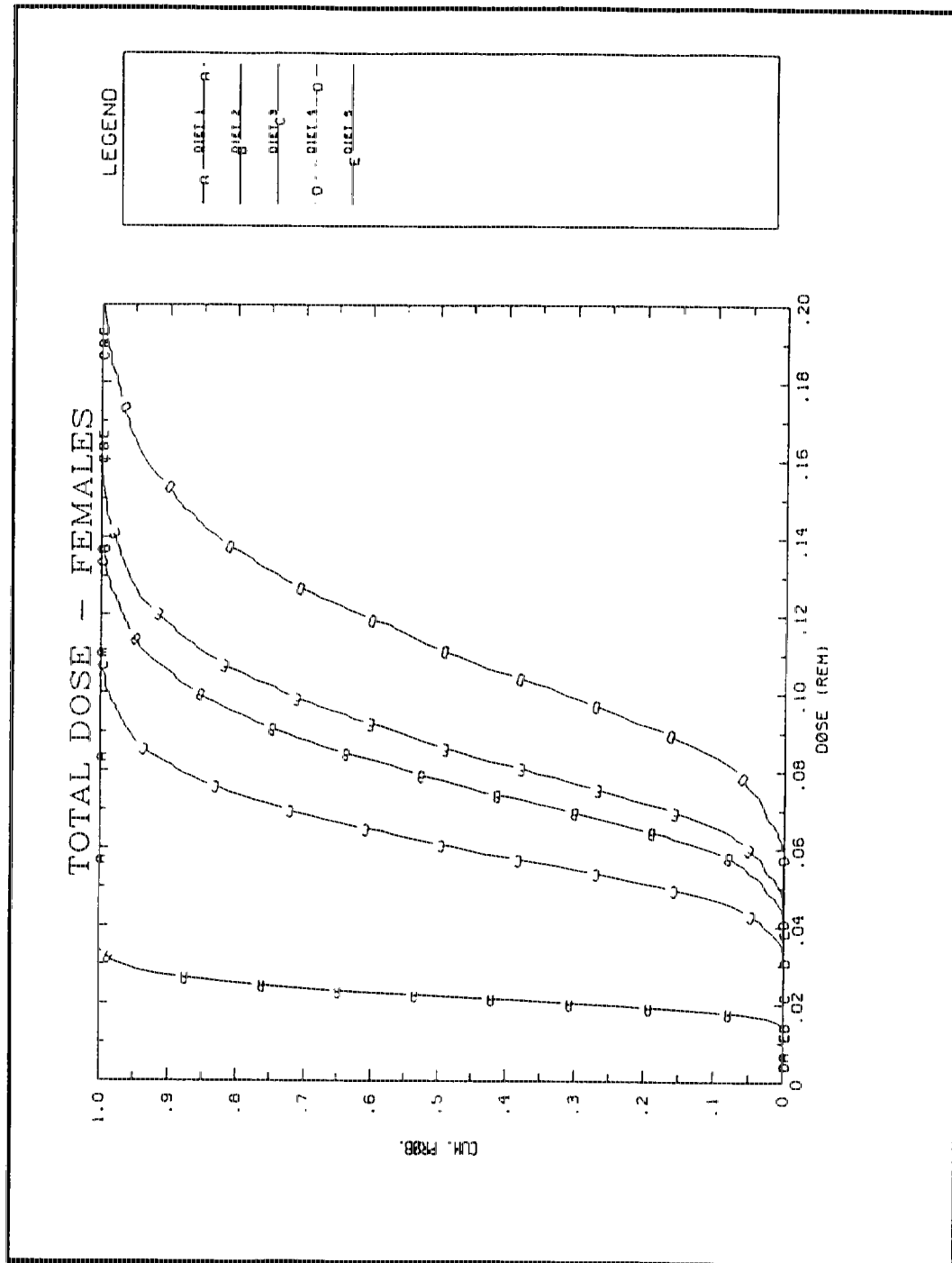


Figure 6
Females: Base Case: Total Dose: Based on S(x)



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Rongelap Resettlement Project

**Extrapolating Future Internal Radiation Doses for Rongelap from
1958-1984 Whole Body Counting Data**

Executive Summary¹

November 1994

Bernd Franke, Scientific Management Team

¹a copy of the complete report with appendices can be obtained from IEER



1 Introduction

A direct way to realistically determine individual variation in the intake of local food items on Rongelap Atoll is the analysis of decay-adjusted whole body counting data from Rongelap residents from eleven mission years during the time period 1957 through 1985. This data allows the determination of annual radiation doses from ^{137}Cs under the following assumptions:

- 1) the body burden for a given individual is representative for the entire year in question;
- 2) the monitored individuals are representative for the entire age and sex group; and
- 3) the decrease of ^{137}Cs in local foods (and thus in the body burden) for Rongelap can be adequately characterized by radioactive decay.

Under these assumptions, the decay adjusted data allows to evaluate the variability of the radiation exposure in the year 1995 if the Rongelap community would resettle on Rongelap and exhibit the same diet pattern as they existed in a particular mission year.

2 Available data

The raw data on whole body counting a total of 1121 separate measurements was received from DOE at the request of the Rongelap Resettlement Project from pre-DOS data files.¹ As indicated in the letter accompanying the data compilation, conflicting information on body weight appears to have been entered into the data base. In some cases, unrealistically high or low body weights were entered at the time of measurements (see Figure 1). Other errors include incorrect coding of sex and age information. In addition, each record does not always represent a different person. For QA purposes, some individuals were recounted in the same chair or counted in a different chair.

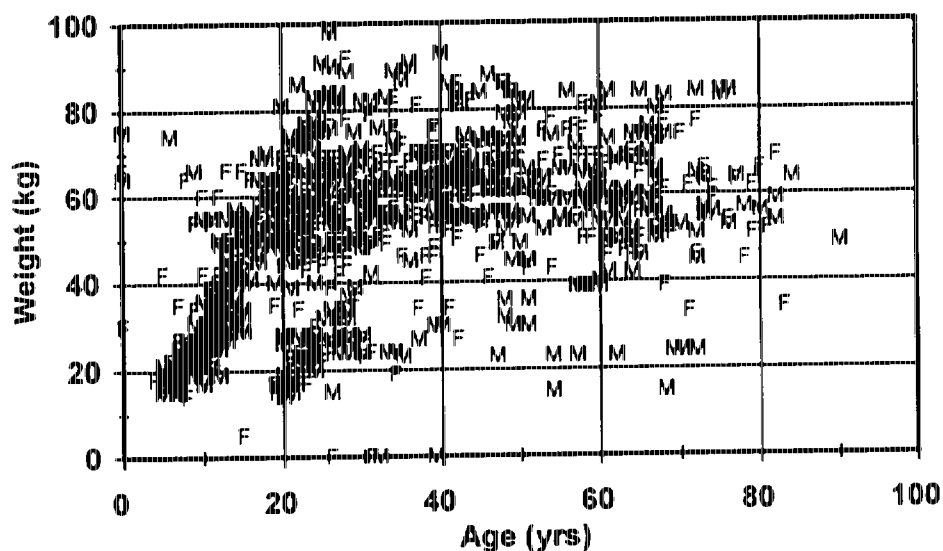
On the basis of the available information these errors could not be corrected. It is obvious that any attempt to use the weight information for dose estimation purposes would lead to highly uncertain results. It was therefore decided to estimate the doses based on data for persons whose age was coded with 18 years and above and to uniformly assume an adult body weight of 66.4 kg as determined in the May 1993 Mejjatto diet survey.

¹ Letter by Harry Pettengill, Deputy Assistant Secretary for Health, U.S. Department of Energy to Bernd Franke, IEER, available from IEER, Wilhelm-Blum-Str. 12-14, 69120 Heidelberg, Germany

Thus, a total of 762 data points or 68% of the original set was used in the analysis. It should be noted in this context that the greatest number of persons whose age is given in the data file with younger than 18 years was monitored in the 1980ies.

The methodology has three main uncertainties: (1) the data set used in the analysis may include data of persons which are actually younger than 18 years but whose age was incorrectly entered, (2) it may contain repeat measurements of the same individual in the same year, and (3) the actual body weight may be larger or smaller than assumed here. As a result, doses may be overestimated or underestimated.

Figure 1 Scatter diagram of data for age, weight and sex as contained in the file with Rongelap WBC data



3 Dose estimation method

For a given activity A in the body, the internal dose from ^{137}Cs is calculated as follows:

$$D = S * A \text{ [Sv/Bq] ,}$$

with

$$S = 1.6 * 10^{-10} * m^{-1} * [0.2311 + 0.5633 * \phi_{\gamma}(m)]$$

$m =$ body mass in g

$\phi_{\gamma}(m) =$ absorption coefficient as a function of body mass

For photons and the short-lived daughter ^{137m}Ba in equilibrium with the parent and a body mass of 66.4 kg, $\phi_{\gamma} = 0.33$; thus

$$S = 1.0 * 10^{-15} \text{ Sv/transformation in total body}$$

Assuming that the body mass and the total body activity is constant over a year,

$$D = S * 3.15 * 10^7 = 3.15 * 10^{-8} \text{ (Sv yr}^{-1} \text{ Bq)}$$

The measured whole body activity was extrapolated to mid-1995 and individual doses were calculated. For each year, the cumulative frequency of the dose distribution was plotted and values for selected percentiles were interpolated.

4 Results and discussion

The results of the analysis are summarized in Table 1 and in Figure 2. The cumulative frequency distribution for the whole body counting data from the 1965 mission is shown in Figures 2 as an example. The average internal dose ranges from a low of 9 mrem/yr (based on 1984 WBC data) to a high of 45 mrem/yr (based on 1965 WBC data). The maximum individual dose is noted for the year 1977 with 108 mrem/yr. The estimates for the various years appear to reflect the availability of imported food items which increased to a maximum in 1979 followed by a time period in which the average body burden (and thus ingestion of local foods) increased .

This observation is in agreement with reports from the Rongelap community that supply from field trip ships decreased in the early 1980ies. Whereas the body burdens reflect ingestion of local food items, the precise origin of the food cannot be reconstructed. It may be the case that some of the high burdens are due to ingestion of local food from the Northern part of Rongelap Atoll.

The analysis of whole body counting data from residents of Rongelap Atoll indicates that internal radiation doses around 100 mrem/yr can be reasonably expected for a few individuals if Rongelap island would be resettled in 1995 and similiar diet patterns were adopted as they existed during the residence period 1958-1984.

Table 1 Internal ^{137}Cs doses for Rongelap residents in the year 1995 extrapolated from whole body counting data for various mission years
(assuming a body weight of 66.4 kg)

Mission Year	N total	N >18 yrs	Min.	Max.	X ₅	X ₅₀	X	X ₉₅
1958	74	69	12	88	15	32	35	60
1959	119	105	5	66	8	22	28	63
1961	94	83	9	97	14	33	36	70
1965	156	141	14	84	14	35	45	79
1974	46	46	11	70	13	24	28	56
1977	62	47	6	108	8	19	21	42
1979	79	37	0	37	1	11	12	19
1981	117	63	1	57	3	14	16	28
1982	102	51	0	65	0	20	19	41
1983	116	50	3	53	6	18	20	39
1984	156	70	2	32	3	7	9	20

Figure 2 Internal ^{137}Cs dose for Rongelap adult residents in 1995 from 1958 through 1984 mission data (based on a total of 762 whole body counting data points of persons 18 years and up in the various mission years, decay adjusted to 1995, assuming a body weight of 66.4 kg)

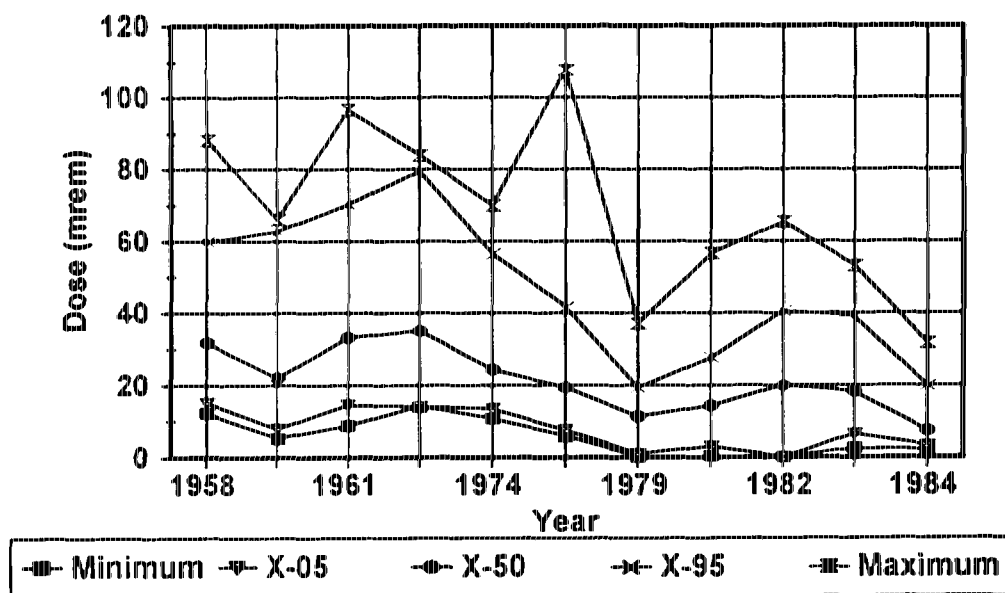
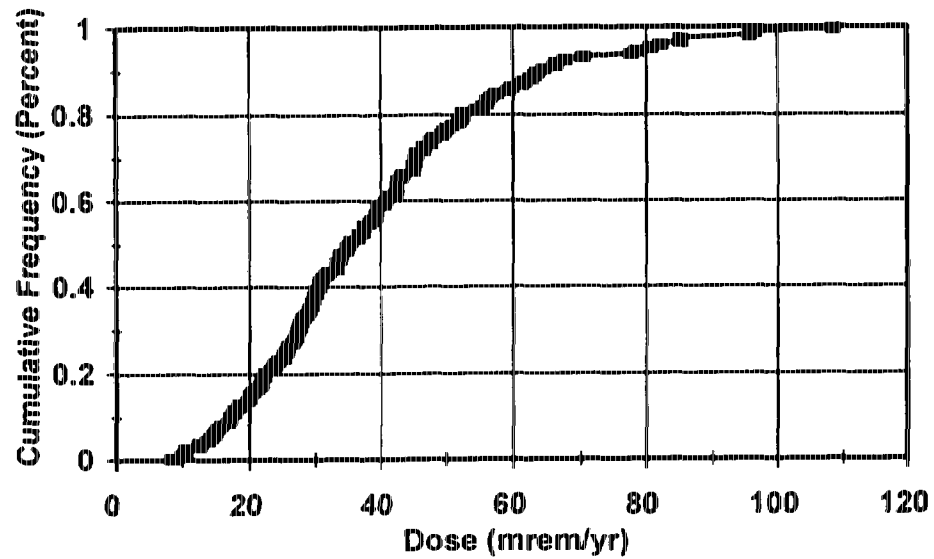


Figure 3

Frequency distribution of internal ^{137}Cs dose for Rongelap adult residents in 1995 from 1965 mission data (based on 141 whole body counting data points of persons 18 years and up in the 1965 mission year, decay adjusted to 1995, assuming a body weight of 66.4 kg)



APPENDIX 6

METHODOLOGY AND RESULTS OF
DETERMINATION OF COMPLIANCE WITH THE LIMIT FOR
TOTAL TRANSURANIC CONCENTRATION IN SOIL OF RONGELAP ISLAND

S. L. Simon
RMI Nationwide Radiological Study

revised
October 1994

METHODOLOGY AND RESULTS OF DETERMINATION OF COMPLIANCE WITH THE LIMIT FOR TOTAL TRANSURANIC CONCENTRATION IN SOIL OF RONGELAP ISLAND

Steven L. Simon

BACKGROUND

A four-way Memorandum of Understanding (MOU) was signed between the Republic of the Marshall Islands Government, the Rongelap Atoll Local Government, the U.S. Department of Energy (Office of Environment, Safety and Health) and the U.S. Department of Interior (Office of Territorial and International Affairs) on 2 February 1992. The agreement, a development from the provisions of U.S. Public Law 99-239 and Nitijela Resolution 1986-62, enacted two limits which must be determined to be in compliance before resettlement of Rongelap should take place. The determination of compliance was the central objective of studies funded by the U.S. Department of Interior to the scientific study, entitled the Rongelap Resettlement Project. The second of these limits refers to the extent of transuranic contamination of the soil.

As stated in ARTICLE II, Section 4 of the MOU:

"An additional condition of mitigation is the extent of transuranic contamination, especially plutonium contamination of the soil. The parties are agreed that this issue, as well as the possible need for an environmental cleanup program solely for transuranic contamination, requires careful deliberation. To this end, it is agreed that the studies undertaken pursuant to the Rongelap Work Plan shall include measurements of transuranics in the environment of Rongelap Atoll, utilizing as an "action limit" the screening level of the U.S. Environmental Protection Agency ("EPA") of 0.2 microcuries per square meter, which has been translated by the DOE/ES&H into an activity concentration of 17 picocuries/gram (pCi/g) of transuranics averaged in the top 5 centimeters (cm) of soil. The "action limit" has been set at 17 pCi/g of transuranics in the soil. Measurement of transuranic contamination in the environment and determination of whether the "action limit" has been met or exceeded will be made pursuant to an appropriate environmental sampling plan developed by the Rongelap Resettlement Project."

DEFINITIONS

Transuranics: Transuranic radionuclides are those seventeen known man-made elements that are heavier than uranium (Seaborg and Loveland 1990), i.e., beyond or "trans-" uranium, the heaviest of the natural elements. Of historical interest is the fact that two of the transuranic elements, Einsteinium and Fermium, were first discovered in the Marshall Islands in radioactive debris from the "MIKE" thermonuclear test conducted on Enewetak Atoll on 1 November 1992. Only isotopes of plutonium and americium, however, are measurable in the environment at Rongelap. Therefore, this assessment defines total transuranic activity to be the sum of 241-

americium (^{241}Am) and 238-, 239- and 240-plutonium ($^{238+239+240}\text{Pu}$). Because the environmental concentration of ^{238}Pu at Rongelap Island is low and near the limit of detectability by alpha spectrometry, it is not reported here.

Soil Density: The bulk soil density, is discussed by Brady (1974) in one of the classic texts of soil science: "In this case, the total soil space (space occupied by solids and pore spaces combined) is considered. Bulk density is defined as the mass (weight) of a unit volume of dry soil." The bulk soil density measures the mass (dry) per unit volume of soil as it is found in the environment, rather than in an artificially compacted state. Most continental surface soils (e.g., clay, clay loams and silt loams) normally have densities from 1.00 to 1.6 g/cm³ though soils which are loose and porous will have lower weights per unit volume. In particular, coral soils may be less than 1.0 g/cm³, particularly when a large proportion of the soil is made of relatively fresh plant detritus.

Action Limit: The EPA (1990) document, though not providing the definitive guidance on compliance limits, provides information concerning their intent for the term "action limit":

"Such a screening level is not intended to be interpreted as a derived intervention level or as a soil cleanup standard to which all sites of transuranium contamination must be decontaminated; instead, when properly applied, it would identify land areas where no additional monitoring is required."

METHODS

Action Limit The RMI Nationwide Radiological Study examined the derivation of the "action limit" as stated in the MOU and found that the translation from $\mu\text{Ci}/\text{m}^2$ to pCi/g is not logically correct. Nevertheless, an "action limit" of 17 pCi/g or 629 Bq/kg was agreed to in the MOU and is used in this evaluation to determine compliance.

The main point of difference between the "action limit" as given by EPA (1990, Volume 2, p. 3-9) and the MOU is that the EPA indicates that the level of 0.2 $\mu\text{Ci}/\text{m}^2$ pertains to the top 1 cm of soil. The MOU indicates that the stated level should be averaged over 5 cm depth which would effectively reduce the "action limit" on a per gram basis by a factor of 5.

The translation of the primary limit suggested by EPA (1990) from units of $\mu\text{Ci}/\text{m}^2$ to pCi/g is simple and depends in a linear fashion on an assumed value for soil density. The possible values of the "action limit" (on a mass basis) are shown below, depending on its interpretation.

$$\begin{aligned} & \bullet \frac{0.2 \mu\text{Ci}}{\text{m}^2} \times \frac{10^6 \text{ pCi}}{1 \mu\text{Ci}} \times \frac{1 \text{ m}^2}{5 \times 10^4 \text{ cm}^3 \text{ (to 5 cm depth)}} \times \frac{1}{1.0 \text{ g/cm}^3} = \frac{4 \text{ pCi}}{\text{g}} \\ & \bullet \frac{0.2 \mu\text{Ci}}{\text{m}^2} \times \frac{10^6 \text{ pCi}}{1 \mu\text{Ci}} \times \frac{1 \text{ m}^2}{5 \times 10^4 \text{ cm}^3 \text{ (to 5 cm depth)}} \times \frac{1}{1.5 \text{ g/cm}^3} = \frac{2.67 \text{ pCi}}{\text{g}} \end{aligned}$$

$$\bullet \frac{0.2 \mu\text{Ci}}{\text{m}^2} \times \frac{10^6 \text{ pCi}}{1 \mu\text{Ci}} \times \frac{1 \text{ m}^2}{1 \times 10^4 \text{ cm}^3 \text{ (to 1 cm depth)}} \times \frac{1}{1.0 \text{ g/cm}^3} = \frac{20 \text{ pCi}}{\text{g}}$$

$$\bullet \frac{0.2 \mu\text{Ci}}{\text{m}^2} \times \frac{10^6 \text{ pCi}}{1 \mu\text{Ci}} \times \frac{1 \text{ m}^2}{1 \times 10^4 \text{ cm}^3 \text{ (to 1 cm depth)}} \times \frac{1}{1.5 \text{ g/cm}^3} = \frac{13.3 \text{ pCi}}{\text{g}}$$

Apparently, the 17 pCi/g value came from an equation similar to case 4 above, except that the soil density was assumed to be about 1.2 g/cm³. The "action limit" as stated in the MOU must be assumed to utilize a 1 cm averaging depth, despite the fact that it explicitly states a 5 cm averaging depth. The "action limit" of the MOU can be re-expressed in terms of SI units as:

$$\frac{17 \text{ pCi}}{\text{g}} \times \frac{1 \text{ Ci}}{10^{12} \text{ pCi}} \times \frac{3.7 \times 10^{10} \text{ Bq}}{\text{Ci}} \times \frac{1000 \text{ g}}{\text{kg}} = 629 \text{ Bq/kg}$$

Soil Parameters: Soil density values were calculated from surface soil samples of 5 cm depth obtained from a grid of measurement sites on Rongelap Island. Each sample was acquired from a defined area and depth and thus, could be used to determine the soil density directly. Soil density values were computed from the dry weights and volumes of 179 soil samples of 5 cm depth. From these samples, bulk density values were calculated from 0.5 g/cm³ to slightly over 1.0 g/cm³, with a mode value of 0.6 g/cm³. Although this value appears relatively low, it is consistent with the porous nature of coral based soils and with data published by Gessell and Walker (1992) from studies conducted in the late 1950's and early 1960's. The soil density will be somewhat greater in the environment due to the normal moisture content.

It is obvious that a higher value for the soil density was used in the conversion of areal activity to mass activity for construction of the compliance limit. However, using a density value greater than that which was observed tends toward the development of a more stringent limit.

Sampling Methodology Rongelap Island and all the southern islands of Rongelap Atoll were surveyed for radioactivity by the RMI Nationwide Radiological Study on a systematic grid with a spacing of 200 m between measurement points. There were 63 sampling and measurement sites (or grid cells) on Rongelap Island. At each site, in-situ gamma spectrometric measurements were made to assess the ¹³⁷Cs inventory, and surface soil samples were obtained for laboratory measurement of ¹³⁷Cs, ²⁴¹Am and ^{239,240}Pu.

To study the variability on a smaller scale than 200 m, four of the 200 m square grid cells were selected for more detailed study: H2, J3, R27 and Q29. Grid cells H2 and J3 were selected to represent the portion of the island that was most intensely utilized by the community, and hence, likely to have been disturbed to a greater degree than other parts of the island. Grid cells R27 and Q29 were selected to represent the portion of the island that was less likely to have been disturbed. Each of the four grid cells were subdivided into twenty-five, 40 x 40 m subcells and a surface soil sample was collected in each as cell at the same time as a gamma spectrometric

measurement was made. This evaluation added another 100 measurements and samples to the data set for Rongelap Island.

The surface soil samples were a composite of three, 15 x 15 x 5 cm deep samples, taken at random within a radius of about 15 m of the gamma detector which was placed in the center of each grid cell. In some grid cells, the sampling and measurement location was offset to avoid an obvious area of disturbance, e.g., the island road, shoreline, large coral rocks, etc.

Analysis Methodology Measurement of ^{137}Cs in the field was accomplished by calibrating the in-situ gamma spectrometer with data supplied by laboratory measurements of samples and with the use of several different types of calculations and models. The conversion of in-situ data to radioactivity inventories is described in detail elsewhere in this report. Americium-241 was, in some cases, detected by the in-situ spectrometer, however, there are two difficulties in using in-situ measurements to estimate soil radioactivity for ^{241}Am . First, because of the low energy of the gamma emission (59.5 keV) from ^{241}Am , it is relatively difficult to properly calibrate the in-situ detector. Second, in many grid cells, the counting times used for the in-situ spectrometric measurements were determined for ^{137}Cs and were not long enough to ensure high precision of the counting data for ^{241}Am . At some locations, americium was undetectable in the given counting time, however, it was detectable at all locations in laboratory measured soil samples. Therefore, the final determination of ^{241}Am inventory in surface soil was done by laboratory analysis of samples.

Laboratory measurement methodology differed for plutonium and americium even though both are alpha emitters. Americium concentration in the soil was determined by laboratory gamma spectrometry of the 59.5 keV gamma emission. Gamma spectrometry measurements were made in the laboratory of the Nationwide Radiological Study on two, hyperpure germanium (HPGe) detectors with low-energy sensitivity extended to less than 20 keV. Plutonium concentrations were determined from laboratory radiochemistry using a technique of microprecipitation onto neodymium fluoride substrate, followed by measurement of alpha emission using passively implanted planar silicon detectors (PIPS) in a computerized alpha spectrometry system.

To confirm the precision of the methods used in the RMI laboratory, the Nationwide Radiological Study laboratory conducted its own interlaboratory comparison with blind sample analysis conducted at four other participating laboratories including Lawrence Livermore National Laboratory, Colorado State University (Department of Radiological Health Sciences), National Radiation Laboratory of New Zealand and GSF Institut für Strahlenschutz (Germany). Results of comparing values measured in the RMI laboratory with intercomparison results for the measurement of ^{241}Am , $^{239,240}\text{Pu}$ and ^{137}Cs were well within acceptable limits. A report of the intercomparison results was furnished to all participating laboratories.

FINDINGS

The findings of the transuranic analysis was used to examine variability within different parts of the island and whether the compliance limit was satisfied on Rongelap Island and the other southern islands of Rongelap Atoll.

Variability The variability of total transuranic concentration ($^{241}\text{Am} + ^{239,240}\text{Pu}$) in surface soil can be expressed by a Sample Coefficient of Variation (σ/\bar{x}). The C.V. was used to rank the data sets from different parts of the island by degree of variation:

$$\text{H2 (CV=0.93)} > \text{J3 (CV=0.78)} > \text{R27 (CV = 0.75)} > \text{Q29 (CV = 0.67)}.$$

The grid cells R27 and Q29 were as expected, somewhat less variable than H2 and J3, however, the difference was probably not statistically significant. A comparison of the variation of the measurements from all the grids is shown at the end of this section (Figure A6.1)

Variability on the five other islands within the southern part of Rongelap Atoll was generally equal to, or greater than that on Rongelap Island. The other island which were sampled are considerably smaller than Rongelap Island and, hence, are more susceptible to wave and storm damage. The higher degree of variation on the small islands may very well be a reflection of these types of disturbances.

Compliance The proportion of data exceeding the "action limit" of 629 Bq/kg was determined for the 200 m grid, the four small grids and for each of the other southern islands sampled. A summary of the findings are shown in Table A6.1 and A6.2.

The most important observation is that only about 1% of the surface soil samples from Rongelap Island exceeded the "action limit". Although technically out of compliance, the small fraction of samples on Rongelap Island which exceed the agreed "action limit" is comforting and argues in favor of very sparse, if any, mitigative actions. Mitigative actions tend to be either environmentally destructive or relatively expensive.

The situation on other islands was somewhat different with over 20% of the samples analyzed from Eniaetok exceeding the "action limit." The fact that Eniaetok is proportionally higher than Rongelap in samples exceeding the "action limit" is not surprising since it is located about 1/3 of the distance (over 10 km) to the northern side of Rongelap Atoll, an area known to have significantly greater level of contamination. A comparison of the variation of the measurements among the other islands is shown at the end of this section (Figure A6.2).

Table A6.1 Results of measurements of transuranic activity in surface soil from Rongelap Island.

	Pu + Am Bq/kg, all of Rongelap Is.	Pu + Am Bq/kg 200 m grid	Pu + Am Bq/kg H2 grid	Pu + Am Bq/kg J3 grid	Pu + Am Bq/kg R27 grid	Pu + Am Bq/kg Q29 grid
Minimum	16.67	16.67	16.67	20.83	54.01	60.09
Maximum	836.24	490.95	745.57	513.06	836.24	461.31
Points	170	62	23	25	25	25
Mean	200.88	215.72	193.19	171.51	244.89	160.53
Median	175.13	211.21	148.94	142.56	215.00	124.13
Std Deviation	146.66	129.05	178.84	134.57	184.54	108.06
Std Error	11.18	16.39	35.07	25.43	34.87	20.42
Coefficient of Variation	0.73	0.60	0.93	0.78	0.75	0.67
Percentage exceeding 629 Bq/kg	1.2%	0%	3.9%	0%	3.6%	0%

Table A6.2. Results of measurements of transuranic activity in surface soil from islands in southern Rongelap Atoll (all units are Bq/kg of ^{241}Am + $^{239,240}\text{Pu}$).

Island Name	Burok	Keroka	Enekan im Batbien	Litoreka	Eneaetok
Alternate spelling	(Burokku)	(Tuʻa)	(Eniran)	(Busch)	(Eniaetok)
Minimum	167.89	96.50	9.86	5.79	59.22
Maximum	974.56	752.13	353.98	272.05	1050.90
Points	5	13	4	5	19
Mean	428.82	289.222	153.5325	102.984	405.09474
Median	302.89	265.33	125.15	78.36	290.72
Std Deviation	315.78	181.14	146.08	110.13	287.85
Std Error	141.22	57.28	73.04	49.25	66.04
Coefficient of Variation	0.74	0.63	0.95	1.07	0.71
Percentage exceeding 629 Bq/kg	20.0%	10.0%	0.0%	0.0%	21.1%

DISCUSSION

Table 1 shows that two of the four grid cells studied with 40 m subsampling distances each had a single sample which exceeded the "action limit". The grid on H2 had one sample of 746 Bq/kg, 18% in excess of the limit. The grid on R27 had one sample of 836 Bq/kg, 32% in excess of the limit. However, none of the samples obtained from the 200 m grid exceeded the limit. This indicates that sampling on the 200 m grid, may likely miss smaller spots of higher than average transuranic radioactivity. It is quite likely that other 200 m grid cells will have some areas of unknown size which also exceed the "action limit." However, based on the data collected thus far, the number of locations exceeding the limit is probably not numerous.

Article II, Section 4(b) and 4(c) of the four-way MOU notes: "If... it is determined that soil concentrations exceed the prescribed action limit, then recommendations as to the need for remedial activity and/or clean-up shall be included as part of the report pursuant to the Rongelap Work Plan.

To the extent that transuranic contamination exists in excess of the prescribed "action limit" but is limited in nature, controllable, and does not impact designated dwelling, food gathering, food growing, and/or recreational areas, then resettlement may ensue while mitigative measures are considered and/or undertaken."

The areas of Rongelap Island which exceeded the limit are not confined to unused areas of the island. The traditional location of the main community on this map is in the cells H2, I2, J2, J3, J4, K4 and K5, however, individual families also lived close to both ends of the island (NE corner and W end). It should also be noted that are locations, in or near the community center, which are near the limit. This is one of several factors that should be considered in the design of mitigative actions.

The results of the sample analysis also indicated that there are locations on three other islands in the southern part of the atoll which exceed the limit (Burok, Keroka and Eneaetok). It should be understood, that only locations from which samples were obtained, can possibly be known to exceed the "action limit". Few samples were obtained on the smaller islands. Thus, all locations which may be in excess of the limit are not known because of limited sampling. An important observation from the sampling program is that the large islands of the southern part of the atoll do have areas which exceed the "action limit".

RECOMMENDATIONS

The concentrations of transuranic activity in the environment of Rongelap Island do not contribute significantly to the annual dose; this will surely be the case for at least several more half-lives of ^{137}Cs (i.e., over 100 years). Therefore, the cost of mitigative strategies should be carefully weighed against other community improvements which might be more cost effective in reducing radiation dose and improving the overall health and welfare of the population. At the

levels of contamination determined, there is certainly no reason for a clean-up program which might be destructive to the environment, e.g., wide-spread soil scraping. However, to the degree that plutonium contamination is a concern for the young and growing population, some cost-effective measures should be designed to reduce the potential of plutonium intake.

In particular, the extensive use of radiologically clean, crushed coral in community areas, around homes and play areas would help reduce contact with the soil, minimize resuspension and other possible routes of entry in the body.

Additional measurements at smaller grid scales, particularly on Rongelap Island, would help better characterize spatial variability and improve our estimates of the portion of the island that truly exceeds the allowed concentration limit.

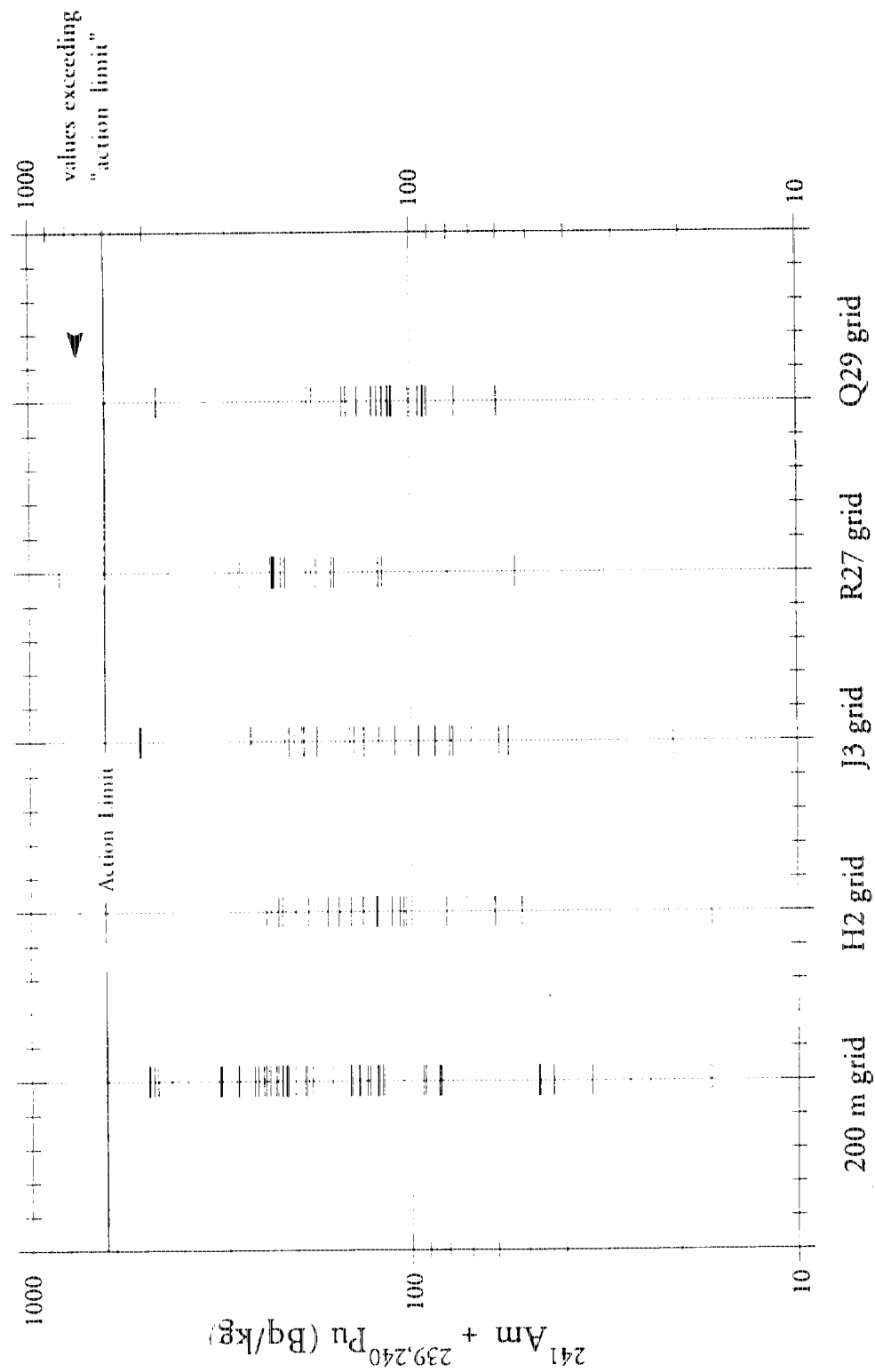
ACKNOWLEDGEMENTS

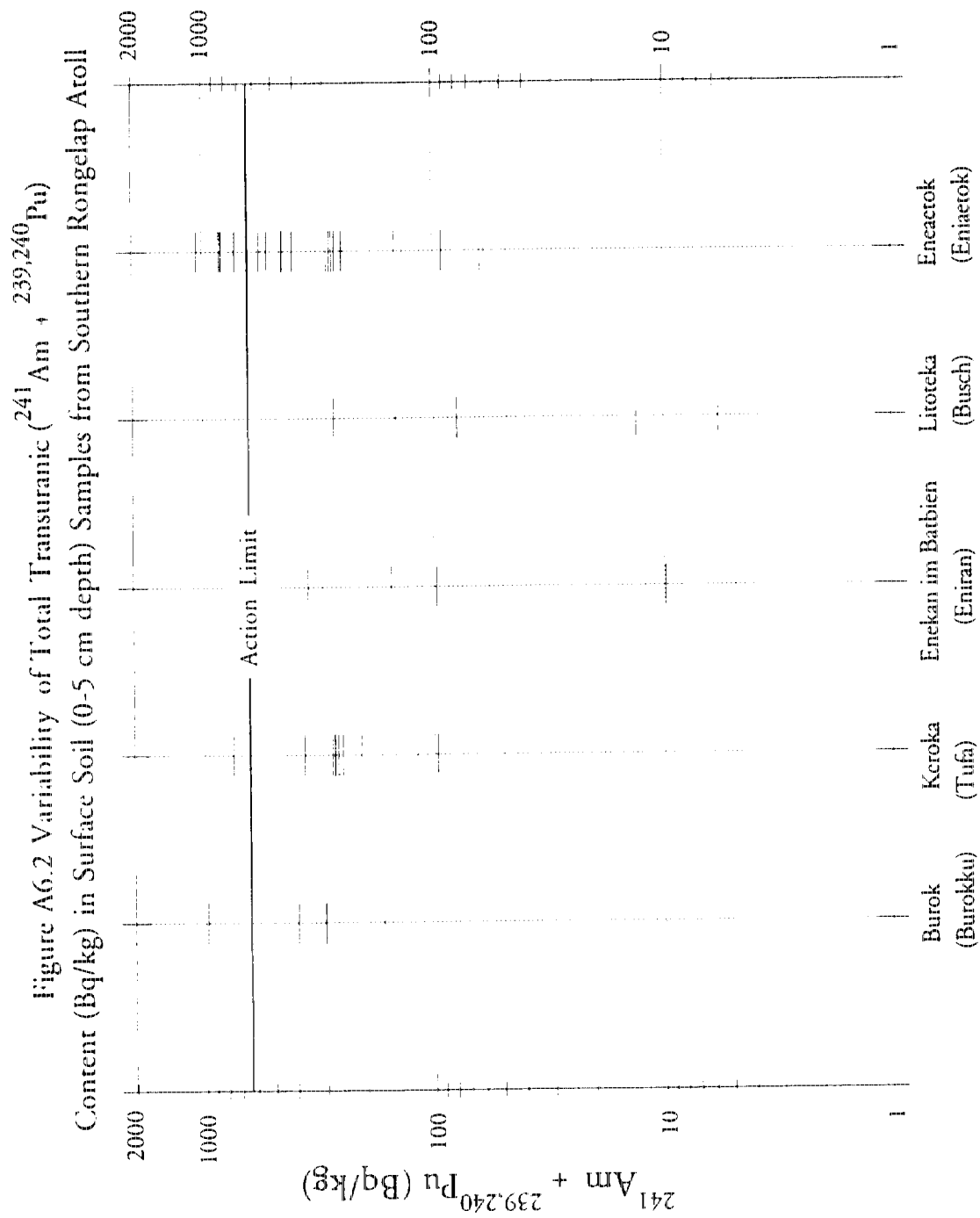
Mr. Andy Borchert, radiochemist for the Nationwide Radiological Study, was responsible for analyses of plutonium in soil. He was assisted by Mr. Randy Thomas of Rongelap and other employees of the Nationwide Radiological Study.

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Figure A6.1 Variability of Total Transuranic ($^{241}\text{Am} + ^{239,240}\text{Pu}$) Content (Bq/kg) in Surface Soil (0-5 cm depth) Samples from Rongelap Island





APPENDIX 7

TRANSURANICS IN BONE OF DECEASED FORMER RESIDENTS OF RONGELAP ATOLL, MARSHALL ISLANDS

EXECUTIVE SUMMARY

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Rongelap Resettlement Project

Transuranics in Bone of Deceased Former Residents of Rongelap Atoll, Marshall Islands

Executive Summary⁷

November 1994

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⁷a copy of the complete report with appendices can be obtained from IEER



Abstract

Rongelap Atoll received intensive fallout from the March 1, 1954, *Bravo* thermonuclear test 105 miles upwind at Bikini. Fearful of their continued exposure to radiation, the residents of Rongelap Atoll went into voluntary exile in 1985. Transuranic soil concentrations on Rongelap Island are about 2 to 3 orders of magnitude greater than the average for the Northern hemisphere; the three dominating transuranics are $^{239,240}\text{Pu}$ and ^{241}Am . Only conflicting information has been available about the extent of transuranic uptake by the Rongelap community. As part of the Rongelap Resettlement Project, the community endorsed the exhumation of bones of deceased former atoll residents to provide an independent estimate of plutonium intake. This approach has the advantage of reducing the uncertainties associated with pathway modeling and the interpretation of urine data.

Six graves (4 adults, 2 children) were selected for exhumation. Femora and tibiae were selected as well as humeri from the children's graves. The rest of the remains was left undisturbed. The results of the analysis of $^{239,240}\text{Pu}$ and ^{241}Am are presented. Assuming that the data can be considered as representative for the Rongelap population as a whole, the contamination with transuranics on Rongelap Atoll appears to result in radiation exposures in the order of 1% of the compliance limit of 100 mrem (1 mSv) effective dose equivalent per year.

1 Introduction

The *Bravo* fallout led to a significant deposition of plutonium and other transuranics on Rongelap Atoll. The three dominant transuranics are ^{239}Pu , ^{240}Pu and ^{241}Am . The median concentrations in the top 5 cm of soil on Rongelap Island are about 70 Bq/kg of $^{239,240}\text{Pu}$ and 40 Bq/kg of ^{241}Am . The actinide concentration is thus two to three orders of magnitude higher than that in most other parts of the world.

Out of 175 pooled samples, two exceeded the transuranic compliance limit of 630 Bq/kg (Baverstock *et al.*, 1994) which was agreed upon in February 1992 (Republic of the Marshall Islands *et al.*, 1992).

For many years, only conflicting information was available about the extent of transuranic uptake by the Rongelap community. Whereas dose estimates based on pathway modeling indicated that plutonium and other transuranics were only minor contributors to the overall dose (Robison *et al.*, 1982), data on plutonium in some 500 urine samples collected in the years 1973, 1976, 1981, 1982, 1983 and 1984 showed elevated levels of plutonium. The urine data was unreliable due to potential contamination of urine samples with soil and problems with the analytical procedures (Sun *et al.*, 1992). The results of 67 urine samples collected in September of 1988 were lower than earlier measurements indicating that soil contamination may have occurred in the earlier samples (Sun *et al.*, 1994).

Determination of transuranic body burden from concentrations in urine is subject to considerable uncertainties due to sampling and analytical errors, day-to-day variations and the uncertainty of the metabolic models. It is therefore the objective of the study to provide, by analysis of bone samples obtained by exhumation of deceased residents, an independent verification of the estimates of plutonium intake via pathway modeling and the results of the most recent analysis of urine from former Rongelap residents. Since about 45% of the initial uptake of Pu into the bloodstream is transferred into the skeleton where it is assumed to be retained with a biological half life of 50 years (ICRP, 1986), analyzing bone tissue for transuranic content has the advantage of reducing the uncertainties associated with pathway modeling and interpretation of urine data. However, the question of the representativeness of the samples and potential cross-contamination with soil has to be addressed.

2 Sampling considerations

Required amount of sampling material

For the purpose of this assessment the analytical procedure and detection method used must provide low detection limits which allow verification of the results of urine analysis. All of the latest urine samples were analyzed with fission track analysis (FTA). The results indicate that the urinary excretion of plutonium was in all cases below 5.5 $\mu\text{Bq/d}$. The majority of samples were below the minimum detection activity concentration of 3 $\mu\text{Bq/d}$.

Since at least three years had passed between uptake on Rongelap Island which ended with the departure in 1985 and the time of urine sampling on Mejjatto, a daily excretion fraction of $1 \cdot 10^{-5}$ of systemic intake appears to be reasonable for the purpose of this assessment (ICRP 54, 1988). Therefore the FTA lower detection limit of 3 $\mu\text{Bq/d}$ is equivalent to a body burden of about 300 mBq. According to ICRP 30 (ICRP, 1979), a body burden of 300 mBq plutonium corresponds with an activity of 135 mBq in the whole skeleton and a concentration of about 14 mBq/kg wet weight or about 48 mBq/kg ash weight.

A second objective in setting the required level of sensitivity was to ensure that not more than a certain fraction (say 10%) of the 100 mrem annual CEDE should be attributable to Pu. In such a case, the resulting uptake according to ICRP 30 would be 83 mBq/yr into the bloodstream. Assuming that a deceased resident has lived on Rongelap Island for 10 years and received 10 mrem/yr CEDE from Pu, a 10 kg skeletal mass and a transfer of 45% of the systemic intake into the skeleton one would expect a bone concentration of about 37 mBq/kg.

The analytical procedure used for bone tissue analysis therefore has to achieve a lower detection limit equal to or below the values mentioned above. The detection method of alpha-spectrometry employed here results in a lower detection limit of 0.3 mBq (confidence level 99.7 %) per sample for $^{239,240}\text{Pu}$ at a counting time of about 10.000 min and a chemical yield of 70%. For ^{241}Am the

lower detection limit is about 0.2 mBq per sample at a counting time of about 10 000 min and a chemical yield of 50%.

To obtain the calculated detection limits of 14 mBq/kg fresh weight or 48 mBq/kg ash weight respectively, a sample amount of at least 20 g fresh weight is necessary.

Selection of exhumation cases

Since exhumations on Rongelap island was ruled out because of the potential severe impact of soil contamination, alternative exhumation sites were evaluated. In order to define suitable and representative cases for exhumation, a survey was undertaken to determine the starting age of residence and the total residence time on Rongelap (post-1957) of those deceased Rongelap residents who had lived on Rongelap and are buried either on Mejatto I. or on Ebeye I. both located in Kwajalein Atoll, more than 100 km south of Rongelap Atoll. Since there is no written record except birth and death certificates which could be used for this purpose, the information was obtained by interviewing Rongelap community members. The result of the survey is shown in Fig. 1. In general, deceased residents of Rongelap buried on Mejatto I. had a longer exposure time on Rongelap than deceased buried on Ebeye I.. The residence time included in several cases the critical years of early childhood where the potential of soil ingestion is higher than in adulthood.

Those deceased former residents who were buried on Mejatto therefore constitute the most relevant cases for the objectives of this study. It was determined by visits of the gravesites on Ebeye and Majuro that any exhumation would cause great disruption to the graves of deceased from other atolls. A total of six graves on Mejatto were selected for exhumation (Table 1). One individual had been exposed in 1954; the remaining six were exposed to residual contamination on Rongelap. Written authorizations were obtained from the family members of those deceased. Death certificates were obtained from Majuro hospital. The residence history of the six individuals was obtained by interview with relatives.

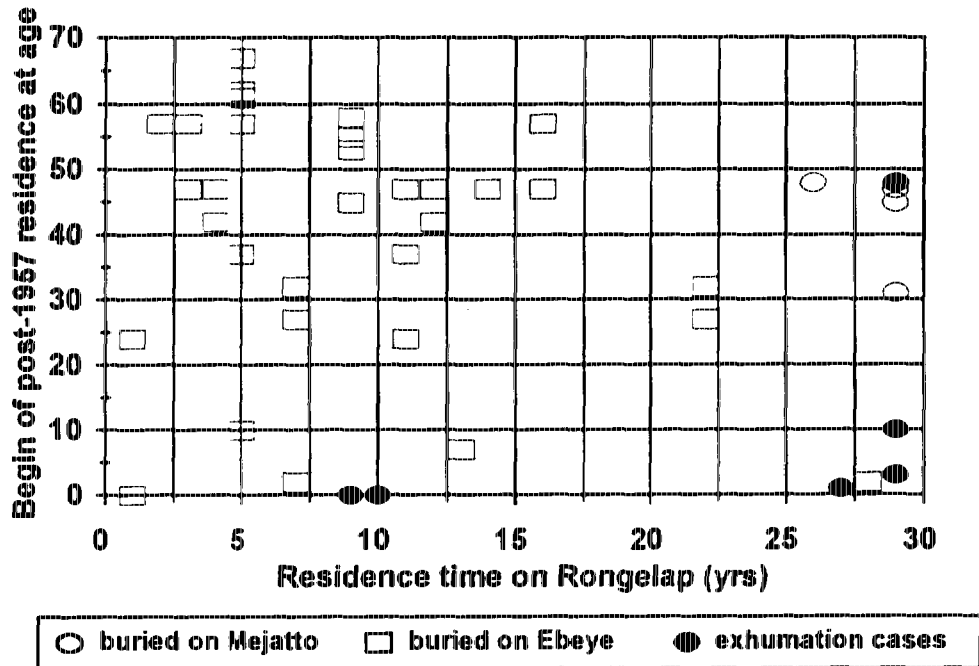


Fig. 1 Exposure history of deceased former Rongelap residents, buried on Ebeye^{*)} and Mejjatto^{**) [*) including one individual buried on Carlos I., **) including three individuals buried on adjacent Ebaddon I.]}

Exhumation

A field trip to Mejjatto took place in January 1993. The exhumations were carried out by and documented using archeological techniques with the objective of minimal intrusion (Spennemann, 1993). A prayer service was held on the Sunday night before the work started; the island minister consecrated each grave after samples were taken. From each grave, three grab soil samples of about 1 kg each were taken: one each from the leg and chest region on top of the coffins and one sample from undisturbed soil at the depth of each coffin. Considerable care was applied in removing all soil from entering the coffins before opening. The top covers of all six coffins were intact and no soil was found inside the coffins. Therefore, soil contamination is considered highly unlikely. Femura and tibiae were selected as well as humeri from the children graves. The rest of the remains was left undisturbed.

Sample preparation

In April 1993, the samples were cleaned, examined, photographed and prepared for further analysis by Prof. Peter Möller of the Institute for Pathology, University of Heidelberg who provided a pathological report. To allow for examination of potential bone diseases, the bones were cut laterally and divided in distal and proximal parts (with the exception of case# 4, where dissection

was done in distal and proximal parts only due to insufficient bone mass). Femora and tibiae of case #2 showed massive athrotic changes, the bones of case #5 were indicative of congenital hip dysplasia, samples from the other cases showed no signs of gross pathology. The bone saw was thoroughly cleaned after each samples was cut. A total of 104 samples were generated. About 25% of the sample mass was ashed and used for the analysis. The samples were dried to constant weight at about 105°C, ashed at 550°C in a muffle furnace, and the weight was determined on wet, dry, and ash basis.

Table 1. Description of the residence history

Case	Sex	Year of Birth	Year of Death	Remarks
#1	F	1947	1986	born on Kwajalein Atoll lived on Rongelap from 1957 to 1985 was away only a few weeks at any one time visited Bikini and Eniwetak
#2	M	1909	1987	was exposed to direct fallout in 1954 lived on Rongelap from 1957 to 1985 since 1960 severe arthritis
#3	M	1954	1988	born on Kwajalein Atoll lived on Rongelap from 1957 to 1972 and from 1978 to 1985 high school visit on Majuro 1972 to 1978
#4	M	1956	1989	born on Ejit Island; lived on Rongelap from 1957 to 1985 with exception of high school visit on Majuro (years unknown)
#5	F	1976	1986	born on Rongelap paralysis, congenital hip dysplasia lived on Rongelap from 1976 to 1985 stayed indoors most of the time
#6	F	1977	1987	born on Ebeye came to Rongelap at age 2-4 months lived on Rongelap from 1977 to 1985

3 Analytical method

Analysis of the bone samples for plutonium, americium and curium was carried out by the Laboratory for Environmental Radioactivity, University of Regensburg, Germany. Alpha spectrometric methods are the most sensitive for to detection of such small activities in human bone.

To obtain highly resolved alpha spectra it is necessary to prepare the specimen as a thin layer. In addition, the elements of interest have to be separated from the sample matrix and from all possibly interfering alpha emitters.

To comply with these basic requirements, analytical procedures were used which combined high chemical yield of the element, high selectivity for interfering alpha-emitters (decontamination factors $>10^4$), justifiable expense and high sample masses (up to 50 g of ashes sample). To correct for individual losses during analysis, chemical yield tracer radionuclides are added to the ashed sample. The analytical procedures for the analysis are described in detail in (Schüttelkopf, 1981 and Afsar and Schüttelkopf, 1981) which are routinely applied to many samples of soil and plant material.

Analytical procedure for plutonium

The radiochemical analysis for plutonium in bone samples starts with the pretreatment of the ashed samples. Up to 50 g of ash is leached by boiling with a mixture of HNO_3/HF for 30 min. After centrifugation and separation of the supernatant solution the residue is leached and boiled again with a mixture of $\text{HNO}_3/\text{Al}(\text{NO}_3)_3$ for half an hour. This procedure assures that all plutonium in the sample solution is converted to the same oxidation state and therefore exhibits the same chemical behavior during the subsequent analytical steps.

The first separation of plutonium is achieved by extraction with triocetylphosphin oxide/cyclohexane. Most of the matrix elements can be separated. Reextraction takes place with ascorbic acid/HCl and a fairly clean plutonium fraction is achieved. The radiochemical separation of disturbing alpha-emitters and residues of the matrix elements consists of LaF_3 coprecipitation and anion exchange. The preparation of the pure plutonium fraction is done by electroplating from oxalic acid/HCl. The decontamination factors are $>10^4$ for polonium, thorium and uranium and $>10^5$ for americium, curium, californium and radium. For chemical yield determination ^{236}Pu was used (Schüttelkopf, 1981).

Analytical procedure for americium and curium

The pretreatment of the ashed samples is done in the same way as described for plutonium. The first separation of americium and curium is achieved by extraction with triocetylphosphin oxide/diethylbenzene adsorbed on Chromosorb. Most of the matrix elements can be separated and a fairly clean americium and curium fraction is achieved. After a further cleaning using a cation/anion exchanger in conc. HCl, the radiochemical separation of the lanthanides consists of an adsorption on anion exchanger in CH_3OH media and a special cleaning step for lanthanides using NH_4SCN in $\text{CH}_3\text{OH}/\text{HCl}$. The preparation of the pure americium and curium fraction is done by electroplating from oxalic acid/HCl. The decontamination factors are $>10^4$ for polonium, thorium and uranium, $>10^5$ for plutonium and radium and about 10^4 for neptunium. The chemical yield for americium is just the same as for curium (Afsar and Schüttelkopf, 1981). For chemical yield determination ^{243}Am are used.

Alpha spectrometry

The method of alpha spectrometry employing silicon surface detectors provides both an excellent energy resolution and an extremely low detection limit due to its very low background counting rate. Thus the isotopes of interest can be identified easily. An example of an alpha spectrum is shown in Fig. 2. The activities are determined by evaluating the alpha peaks of the transitions of interest and comparing them with the peak of the chemical yield tracer. The alpha spectrometer device employed consists of a silicon surface barrier detector in an Alpha-King-Spectrometer Model 676 (EG&G Ortec) with 900 mm² active surface and a resolution of 21 keV at 5.486 MeV (²⁴¹Am). The alpha specimen is mounted on a sample holder and inserted into the alpha chamber to achieve the nearest possible distance between sample and detector.

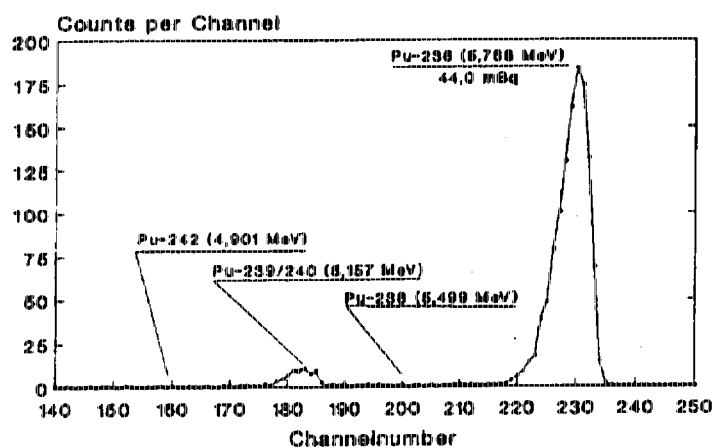


Fig. 2 Alpha spectrum of bone sample #2. The peak of ^{239,240}Pu is significantly above background with a counting time of about 11 000 min.

Lower detection limit

The tracer isotopes cause a pronounced increase in the background counting rates in the regions of the alpha energies of the nuclides of interest. In addition, ²³⁶Pu contains small amounts of ²³⁸Pu (about 1% of the tracer activity) which causes a further increase in the background counting rate. It has been further proven that both the apparatus and the used chemicals are free from any contamination. It is therefore necessary to calculate the detection limit on the basis of the data calculated from blank spectra where only the chemical yield tracer is analyzed. Thus an analysis of the tracer nuclide is done before each single analysis of a bone sample.

Beta spectrometry of ²⁴¹Pu

²⁴¹Pu with a half-life of 14.4 years decays into ²⁴¹Am emitting beta particles with a mean energy of 5.236 keV. The most convenient and sensitive method of detecting ²⁴¹Pu is the method of liquid scintillation counting (LSC). The sample is analyzed by the plutonium procedure described above.

The preparation containing ^{241}Pu for alpha spectrometry has to be dissolved by about 0.1 ml of conc. nitric acid. The solution is diluted with about 10 ml of water and then mixed with the organic scintillator cocktail Quick Scint 400. For liquid scintillation counting the low level LSC Quantulus 1220 (LKB Wallac) is employed. Active shielding combined with passive ones result in a very low background counting rate of about 1.1 counts/min at the region of interest for ^{241}Pu . The counting efficiency is about 0.27 counts/decay. The detection limit is about 15 mBq/sample ranging from 4 to 19 mBq at a counting time of 1000 min.

4 Results

The wet, dry and ash weights of the samples are shown in Table 2. The lowest (ash weight)/(dry weight) ratio was observed for sample #3 which is in agreement with the observed state of decay of the tissues. The results of the radionuclide analysis are summarized in Table 3.

In Table 4 the $^{239,240}\text{Pu}$ concentrations in bones of former residents of Rongelap Atoll are compared with data for bones from different places in the Northern and Southern hemisphere due to nuclear weapons fallout. One should note that the concentrations of bones in younger people is much lower than that in older ones (Bunzl *et al.*, 1985).

Table 2. Wet, dry and ash weight of analyzed samples

Sample	Wet Weight, WW <i>g</i>	Dry Weight, DW <i>g</i>	Ash Weight, AW <i>g</i>	AW/DW
#1-D	202.9	137.5	78.0	0.57
#2-D	183.5	136.3	91.0	0.67
#3-D	339.2	256.9	128.5	0.50
#4-D	295.8	248.4	142.3	0.57
#5-A	58.9	39.9	23.2	0.58
#6-A	168.0	111.6	74.6	0.67

Table 3. Concentrations of plutonium, americium and curium in bone tissue samples (rounded), bdl=below detection limit

Sample	Nuclide	Specific Activity mBq/kg (ash wt.)	Detection Limit mBq/kg (ash wt.)
#1-D	²³⁸ Pu	bdl	7
	^{239,240} Pu	17 ± 2	3
	²⁴¹ Pu	bdl	230
	²⁴¹ Am	19 ± 8	15
	²⁴² Cm	bdl	6
	²⁴⁴ Cm	bdl	10
#2-D	²³⁸ Pu	bdl	5
	^{239,240} Pu	46 ± 4	5
	²⁴¹ Pu	bdl	140
	²⁴¹ Am	15 ± 6	12
	²⁴² Cm	bdl	7
	²⁴⁴ Cm	bdl	8
#3-D	²³⁸ Pu	bdl	7
	^{239,240} Pu	7 ± 2	4
	²⁴¹ Pu	bdl	240
	²⁴¹ Am	bdl	7
	²⁴² Cm	bdl	3
	²⁴⁴ Cm	bdl	4
#4-D	²³⁸ Pu	bdl	4
	^{239,240} Pu	8 ± 2	4
	²⁴¹ Pu	bdl	540
	²⁴¹ Am	8 ± 4	6
	²⁴² Cm	bdl	4
	²⁴⁴ Cm	bdl	4
#5-A	²³⁸ Pu	bdl	25
	^{239,240} Pu	bdl	18
	²⁴¹ Pu	bdl	1,500
	²⁴¹ Am	bdl	17
	²⁴² Cm	bdl	9
	²⁴⁴ Cm	bdl	11
#6-A	²³⁸ Pu	bdl	10
	^{239,240} Pu	bdl	6
	²⁴¹ Pu	bdl	400
	²⁴¹ Am	bdl	9
	²⁴² Cm	bdl	7
	²⁴⁴ Cm	bdl	7

Table 4. Plutonium concentration in bones due to nuclear weapons fallout in different places

Place of sampling	Time of sampling	Activity concentration (mBq $^{239,240}\text{Pu}$ /kg ash)	Source
New York City	1972 to 1974	14 to 143	Fisenne <i>et al.</i> , 1980
Nepal	1977 to 1978	10 to 74	Fisenne <i>et al.</i> , 1983
Australia	1977 to 1978	13 to 22	Fisenne <i>et al.</i> , 1983
Germany	1980 to 1981	1 to 34 ^{*)}	Bunzl <i>et al.</i> , 1985
Rongelap Atoll	1993 (this study)	< 6 to 46	

^{*)} assuming an ash weight/fresh weight ratio of 0.28

Assuming that there was a more or less constant uptake of $^{239,240}\text{Pu}$ during the residence time on Rongelap, the annual uptake of plutonium can be calculated for each of the six cases. Based on the data in Table 3 and assuming 28% ash content in fresh bones (ICRP 23, 1975), an effective half-life of 50 years for plutonium in bones (ICRP 48, 1986) and the information about residence times on Rongelap Atoll the average annual uptake in bones was calculated. For case #4 it was assumed that the high school visit occurred at the same age as in case #3.

The concentration of transuranics in mineral bone can be used directly to estimate dose rates to mineral bone. The total skeletal weight of the reference male is given with 10 kg, of which 5 kg are mineral bone tissues and 5 kg other tissues (red and yellow marrow, skeletal cartilage and periarticular tissue). The mineral bone tissue itself has a water content of 17% and an ash content of 54%. Since the dry weight of the bone tissues measured include bone marrow and cartilage tissues as well, depending on the stage of decay, the mineral bone concentrations were estimated from the ash weight assuming that the ICRP Publication 23 (ICRP, 1975) ash content of 54% is applicable in all cases.

The dose conversion factors used are based on ICRP dosimetry using a compilation provided by Thorne (1992). The inherent assumption is that the metabolic characteristics of transuranics as implied in the ICRP model such as equal partitioning of the systemic intake between the skeleton and the liver are applicable for each individual from the Rongelap population.

At a given concentration of transuranics in bone tissue, the highest annual doses are estimated for the year of uptake. The measured concentrations in bone were used to estimate doses assuming a single uptake in the first year of potential exposure (taken to be 30 years before death for case #1,2,3,4,7 and 10 years for case #5 and 6). Maximum annual doses in the case of continuous intake would be lower than the doses estimated here.

Table 5. Estimated annual uptake of $^{239,240}\text{Pu}$ in bones for cases #1 through #6

Case	Estimated average annual uptake $\text{mBq kg}^{-1} \text{ a}^{-1}$ wet bone tissue
#1	0.21
#2	0.55
#3	0.10
#4	0.13
#5	<0.52
#6	<0.21

On this basis, the dose estimates in Table 6 represent upper limits of the annual doses from the intake assuming ICRP dosimetry. It should be noted that the application of weighting factors in ICRP 60 leads to effective doses which are up to a factor of two smaller than the doses based on the weighting factors according to ICRP 26.

The potential pathways of uptake are inhalation of resuspended material in air, ingestion of food, and ingestion of soil. The relative contributions of these pathways could not be determined from this study. In the further course of the Rongelap Resettlement Project, the soil intake by children on Mejjatto I. will be determined using elements which naturally occur in soil as tracers.

Table 6. Bone surface and effective doses (mrem/yr) in the first year of potential exposure on Rongelap assuming a single uptake of $^{239,240}\text{Pu}/^{241}\text{Am}$ at the earliest year of potential exposure

Case	Earliest Uptake yrs Before Death	Latest Uptake yrs Before Death	Bone Surface Dose mrem in 1st yr	Effective Dose ICRP 26 mrem in 1st yr	Effective Dose ICRP 60 mrem in 1st yr
#1	29	1	17	1.0	0.6
#2	33	2	28	1.6	1.0
#3	31	3	6.5	0.4	0.2
#4	32	4	7.4	0.4	0.3
#5	10	1	< 12	< 0.7	< 0.4
#6	10	2	< 5.3	< 0.3	< 0.2

5 Discussion

The Rongelap samples exhibit concentrations in a range comparable with that found in samples from non-occupationally exposed persons from other areas in the world.

The estimated doses are small and for all individuals exposed to residual fallout only do not exceed 1 mrem effective dose (ICRP 26 weighting factors applied) in the first year of exposure, even if conservatively a single uptake is assumed. Only the single individual (case #2) who was also exposed to direct fallout from *Bravo* in 1954, had an effective dose of 1.6 mrem if the total intake is assumed to have occurred in the first year of exposure.

Assuming that the data can be considered to be representative for the Rongelap population as a whole, the contamination with transuranics on Rongelap Atoll appears to result in radiation exposures in the order of 1% of the compliance limit of 100 mrem effective dose equivalent per year.

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APPENDIX 8

STUDY OF THE MICRODISTRIBUTION OF PLUTONIUM IN SOIL

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STUDY OF THE MICRODISTRIBUTION OF PLUTONIUM IN SOIL

BACKGROUND

The Importance of the Understanding Characteristics of Plutonium in the Soil

There are various pathways by which humans can receive radiation dose from radionuclides in the environment or by which their bodies can become contaminated with radionuclides present in the environment. It is well known, for example, that plutonium in the terrestrial environment resides primarily in the soil and in sediments in the aquatic environment. Since plutonium is not efficiently transferred into plants via root uptake, the routes of contamination to man are mainly limited to ingestion of plants whose surfaces are contaminated, ingestion of soil directly or inhalation of soil particles. Other minor routes of exposure also exist, e.g. contamination of wounds, etc., however, all such pathways depend on direct or indirect contact with the contaminated soil.

The concentration of plutonium can be measured in soil via radiochemical analysis and alpha spectrometry, however, this type of measurement represents an estimate of the average concentration of the volume of soil analyzed. No information is produced by this kind of analysis to indicate the degree of spatial uniformity of the plutonium in the soil matrix, i.e., whether there are numerous "hot particles" or whether the activity is distributed uniformly throughout. Moreover, no information results from radiochemical analysis concerning the size of the plutonium bearing soil particles.

Information concerning particle activity and spatial uniformity are generally not used directly in a dose assessment, however, this type of information can increase our understanding of the potential risks of pathways which are inherently difficult to evaluate. For example, many questions can be asked which are generally not considered in dose assessments, e.g. 'How does the risk of inhalation compare with that of soil ingestion?', 'Is the risk of inhalation any different near the ground level where children play?' or 'What is the likelihood of children, encountering by chance, hot particles in the soil which are then transferred to their mouths from dirty hands?' It can be argued that these questions are not only difficult to answer, but may depend on the size of plutonium particles and their spatial distribution. This study is intended to examine the questions of particle size and spatial distribution and in doing so, provide supplementary information to other studies which are attempting to more directly evaluate the potential dose to returning residents of Rongelap.

STUDY OBJECTIVES

The initial objectives were to examine the micro-characteristics of plutonium in soil from Rongelap Island. At the onset of the study, the objectives that could be achieved with the available technology were not precisely known. Those objectives which were of interest included:

- (1) the distribution (statistical) of sizes of soil particles containing plutonium,
- (2) the distribution (statistical) of activities of plutonium particulates,
- (3) the spatial microdistribution of plutonium particulates at single sites,
- (4) the uniformity of the microcharacteristics at different sites on the island.

These objectives were met to various degrees during the conduct of the work reported here. Some detailed findings are presented in the second part of this section. Further work is underway at time of this writing and will possibly continue in an effort to address all the questions noted above.

DEFINITION OF SAMPLES

The soil samples which were collected for possible track-etch analysis for characteristics of the microdistribution are surface samples from the 65 locations of the coarse (200 m) grid and the 100 locations from the four fine grids (4 cells with 25 locations each on a 40 m grid). Each of the 165 soil samples are a composite of three subsamples taken from an area within a radius of 10 m; each subsample was approximately 15 x 15 x 5 cm (depth). Each of these samples has been measured by radiochemistry/alpha spectrometry for average concentration of $^{239,240}\text{Pu}$ and ^{241}Am (as well as for gamma emitters, e.g. ^{137}Cs).

TRACK VISUALIZATION SYSTEM

Nearly a year (mid-1992 to mid-1993) was spent in determining the type of instrumentation needed to conduct this study, determining instrument specifications and completing a prototype instrument. An image analysis system was installed in the Majuro laboratory in July of 1993, however, software development continued for several months after installation.

The system was built using expertise of three different companies through a subcontracting arrangement with the main vendor, Scientific Instruments, Inc., a representative of the microscope division of Olympus Corporation (U.S. based company of Olympus Optical Co., Ltd. of Japan).

The prototype system is a combination of off-the-shelf microscope hardware, computer components, image analysis software, specialized imaging hardware and custom programming. A component diagram of the imaging system is enclosed (see Figure 1). The hardware components include:

(1) DELL™ 450/M computer based on the Intel™ 80486, 50 MHz DX2 chip, video display terminal is used for viewing the instruction windows of the image processing application.

(2) Sony GVM-1311Q Trinitron™ 13" color video monitor for viewing the video input from the microscope.

(3) Hewlett-Packard LaserJet 4™ printer capable of providing good quality replications of video and microscopic images using hardware described below.

(4) LaserPix 5.0™: a combination of hardware and software that directs the HP4 laser printer to print at 1200 dpi

(5) SHARP GPB-1™ image processing board: a hardware/firmware combination; that functions as a image grabber and image processing computer for over 50 image processing functions which are addressable by C code.

(6) Olympus™ BHSM transmitted/reflected light, microscope with differential interference contrast (DIC).

(7) Hitachi™ KPM-1 black and white CCD video camera.

(8) Optimas 4.02™ software by Bioscan of Edmonds, Washington: a MS-Windows™ based digital image analysis software application. Optimas supports the SHARP GPB-1 and has a built-in MACRO recording capability and a proprietary image processing language.

(9) Motorized x-y positioning microscope stage with software drivers, etc.

Custom programming to link the motorized stage and the SHARP board with Optimas and to create the custom designed track counting algorithm was carried out by Visioneering Research at New Mexico State University in Las Cruces, New Mexico. Programming uses both the ALI language and source code written in the C language and compiled with the Borland™ Turbo C++ compiler.

System speed was evaluated and is described in the enclosed publication. In short, scanning (including counting of single tracks) could be completed at the approximate rate of 0.69 seconds/FOV.

Data management requirements were also evaluated in these tests. In the speed benchmarking tests, 199 fields-of-view (FOVs) were scanned. Each FOV was 1.313 mm on a side (with a 10x objective). Data from the scan was written to a Microsoft EXCEL™ data file. The file from the 200 FOVs was 427k bytes in size.

Instrument Usage: Calibration of the image field-of-view (FOV) is accomplished by imaging an reflective graticule of 1 mm total length with subdivisions of 0.01 mm (10μ). A line is drawn with the mouse on the video screen equal to the length of a portion of the graticule which is visible. Then length of the segment is then input to OPTIMAS. Each microscope objective is calibrated separately.

Track images are currently being imaged in reflected light only. Reflected light imaging takes advantage of the fact that the tracks are true surface defects after the etching. Tracks on either

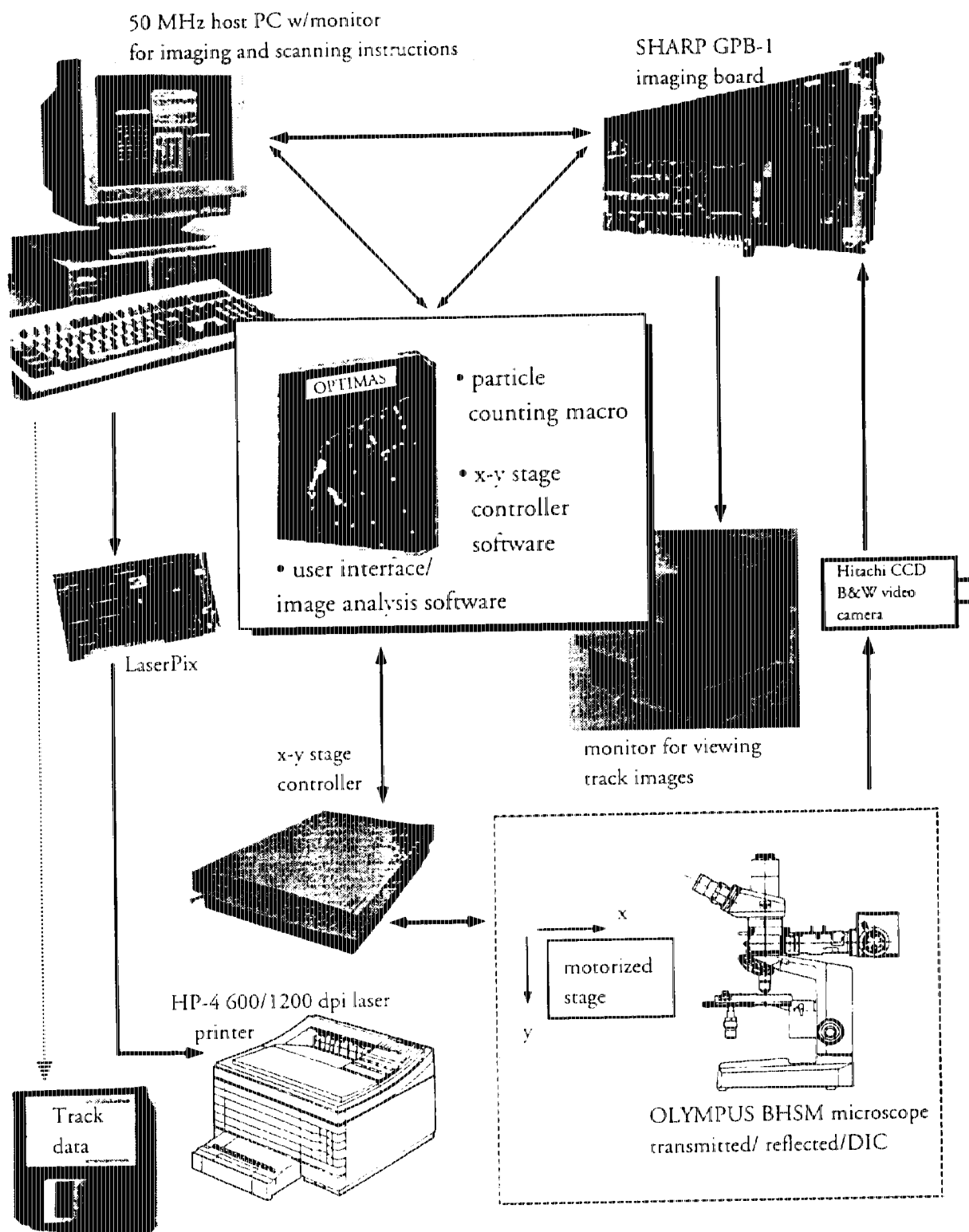


FIGURE 1.
Component Diagram of Alpha Track Counting System
(NWRS/RRP 9/26/93)

side of the plastic can be imaged with relatively little image degradation from tracks on the other side. Differential interference contrast (DIC) with a Nomarski prism is used to determine the exact point of focus on the plastic surface.

An track counting macro ("ALPHA") has been added to the menu of utilities within the OPTIMAS interface. "ALPHA" is currently set up to control the motorized x-y stage and to generate files of data containing the spatial locations and sizes of tracks on the plastic track detectors.

The plastic track detectors are raster scanned to cover the usable area, beginning with one field-of-view (FOV) in one corner and ending with the FOV in the opposite diagonal corner. The size of the FOV is a function of the magnification of the microscope; with the 10x objective, the total magnification is about 17x. The dimension of the FOV with the 10x objective is 1.30 mm (± 0.02 mm) square. The number of FOVs to be scanned on each track detector is set by the operator; most scans contain a minimum of 100 FOVs (1.7 cm²).

A critical step in the track counting operations is the setting of the luminance threshold. The setting of the luminance threshold will, in many cases, determine the effectiveness of counting algorithms because the objects are identified, not by size or shape, but by luminance value.

Data Collection: The track counting macro is designed to be run in two different modes: FAST SCAN and CLUSTER SCAN. The FAST SCAN is run first for the purpose of counting individual tracks, for storing locations and sizes of individual tracks and for saving location data of possible clusters. The FAST SCAN generates two files, one for the user and one binary file. These files are named: "xxxx.hit" and "xxxx.cls". The file "xxxx.hit" contains the track location and size of individual tracks; the data for each FOV is presented in its own column.

The CLUSTER SCAN is run using the binary file "xxxx.cls" to guide the microscope stage back to the location of the clusters. This file can be invoked at any time after the FAST SCAN has been run. The first time it is called, it guides the stage to the (approximate) location of the cluster and draws a contrasting colored "mask" in the shape of the cluster, over the track image. The operator must then compare the shape of the mask to the object on the screen and make a determination if the identified object is a cluster or not. The operator can then "accept" or "reject" the object by clicking the computer mouse. Following the review of the "clusters", a file named "xxxx.txt" is written which contains the x,y location data of the clusters, the FOV number and the area of each cluster.

The "xxxx.hit" file contains a number of data columns, each column containing data for a single FOV. The columns are placed in the file in order of the raster scan and equals the number of FOVs. Each column has three values presented in order: (1) the x-coordinate of a track, (2) the y-coordinate of a track, and (3) the area of a track. This data triplet is repeated down the length of the column for all the tracks in the FOV. Thus the number of non-zero entries in a single column is equal to three times the number of tracks in the FOV plus a single entry at the very bottom of the column giving the total number of tracks in the FOV.

Because the track detectors are exposed to soil containing plutonium on both sides, each side has a unique pattern and may be scanned and analyzed separately. Thus, six computer files are usually generated from each plastic.

Only a certain size of objects are reported in the "xxxx.hit" file. Presently, only objects larger than 0.0001 mm^2 and smaller than 0.0036 mm^2 are reported in the "xxxx.hit" file although both parameters may be changed by the user. Excluding smaller objects eliminates the reporting of insignificant surface defects as tracks. The locations of objects detected during the scan which are larger than 0.00036 mm^2 are recorded as they may represent a "cluster" of tracks from an aggregate of radioactivity in the soil. The size, frequency of occurrence, and spatial relationships of aggregates of radioactivity are of fundamental interest of this study.

The location data of the tracks is measured from an arbitrary point of origin on the plastic. Prior to the scan, we make a permanent scratch in the form of an 'X' on both surfaces in a corner near where an identifying number is also scratched onto the surface. This 'X' is brought into view on the computer screen and is marked as the 'origin' with the mouse. Thus, by referencing the same point of origin and using the "xxxx.cls" file, one can find the clusters on the plastic at any time in the future without rescanning it. All track locations are measured relative to the marked origin point. Usually the origin is outside the area to be scanned but that is not of consequence. The origin is simply a point from which relative measurements can be made. All location data is in units of mm as measured from the operator specified origin. The value of the origin is twofold: (i) it provides a coordinate origin for which the computer can use to return the stage to the coordinates of track clusters for inspection, counting, etc. and (ii) the location data can be used for various types of statistical analyses, plotting, etc.

Each filename from a FAST SCAN and CLUSTER SCAN are composed of the following parts: Track Detector #, Sieve pan size, Side A or B and appended with .hit or .cls. Soils are currently being sieved into different size fractions before exposing the plastic track detectors. The pans sizes (100, 200, 300, pan) refer to the mesh number or fineness of the sieve screens and the "pan" refers to the finest fraction which passes through all three screens and is collected in a pan. For example, filename 2100a.hit refers to track detector number 2 (a code for a particular soil sample), sieve pan 100, side A and ".hit" refers to the file for individual tracks. The first set of plastics have been exposed to Rongelap island soil which was sieved into four different particles size fractions: $180\text{-}150\mu$, $150\text{-}75\mu$, $75\text{-}40\mu$, and $<40\mu$.

Exposure Protocol for Track Detectors

(1) Exposure time is estimated according to the following method. Soil from Rongelap island was determined experimentally to require about 28 d exposure. This interval provides enough individual tracks to obtain statistically significant counts in each FOV while not overexposing many clusters so as to be excessively dense. Exposure time for plastics from other locations were scaled based on the estimated Pu concentration. The Pu concentration was either known from

alpha spectrometry measurements or was approximated from ^{241}Am measurements made by gamma spectrometry:

$$\text{Estimated Pu (new location)} = \frac{\text{Pu concentration (Rongelap Island)}}{\text{Am concentration (Rongelap Island)}} \times \text{Am (new location)}$$

$$\text{Approximate exposure time} = 28 \text{ d} \times \frac{\text{Pu concentration (Rongelap Island)}}{\text{Pu concentration (new location)}}$$

(2) Soil is dried. This step was carried out as part of the soil preparation steps for gamma spectrometry in the laboratory.

(3) 100 g of soil for track analysis is removed from the sample (the remainder to be analyzed by gamma and alpha spectrometry).

(4) The 100 g aliquot is sieved into different particle size fraction.

(5) A separate track detector (approximately 3 cm x 3 cm) is covered with soil from each particle size fraction in a cup and placed in a secure location in the laboratory.

(6) When exposure period is complete, track detectors are etched in 6.25 M NaOH solution at 75° C for 6 h.

(7) Track detectors are washed with water, dried, inspected, cleansed in an ultrasonic bath containing mild soap solution, rinsed, immersed in alcohol and air dried.

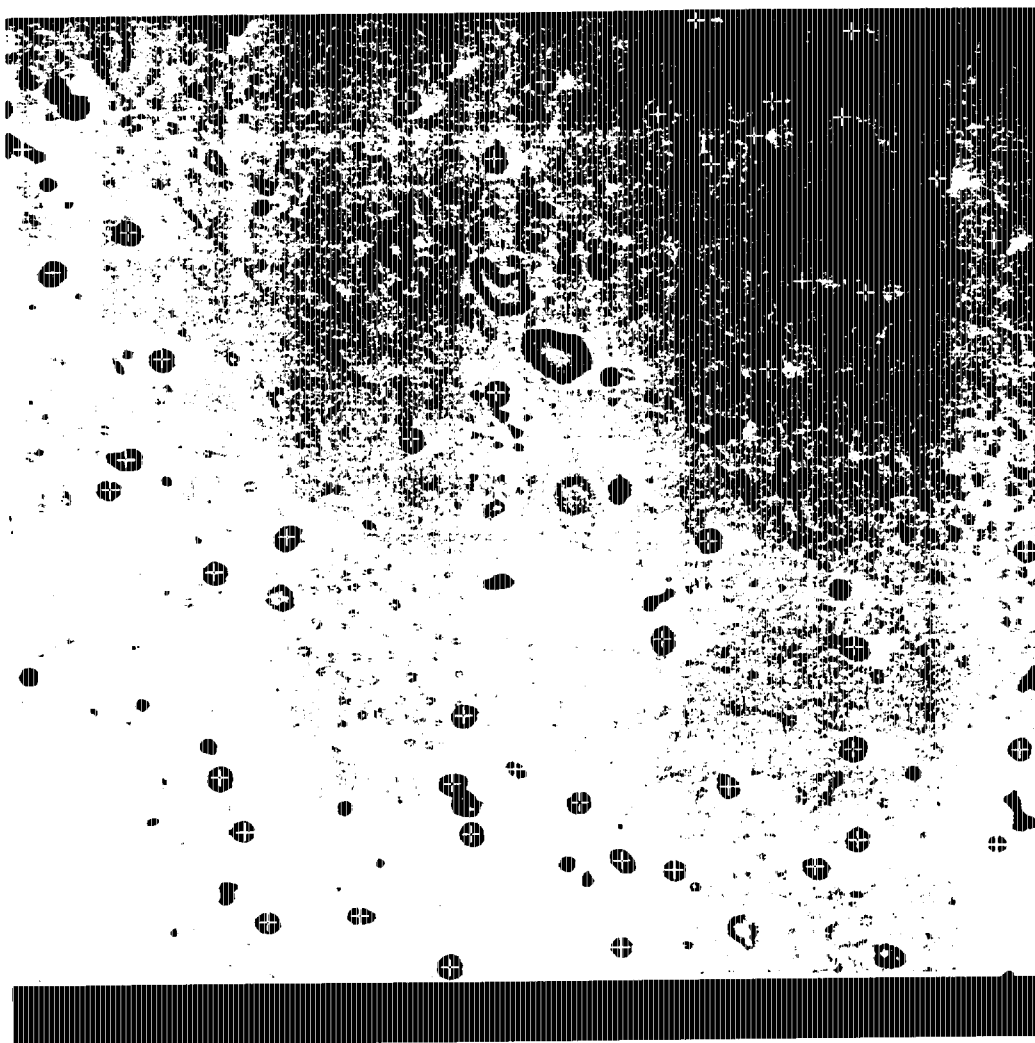
(8) Track detectors are studied with the image analysis system: individual tracks are counted number, location and size of clusters are determined, and data is compiled for further study.

Control Samples

Control track detector samples are needed to detect three types of possible confounding data. These include: (1) defects in the plastic which may appear as alpha tracks, (2) alpha tracks originating from radon daughter exposure at locations previous to the Marshall Islands, and (3) alpha tracks which originate from background alpha radioactivity (natural or fallout) in the soil. Samples of Tastrak CR-39 material¹ were etched in both new condition and after exposure to soil from Majuro (as a control location). The following conclusions were reached regarding the need for control track detectors.

Track detectors which are not carefully handled will usually be found scratched when examined under the microscope. However, most scratches can be eliminated from counting by proper luminance thresholding. With careful handling, this problem is not significant. Figure 2 shows an example of track counting in the presence of minor image noise.

¹obtained from Track Analysis Systems Limited, Bristol, U.K.



Example of counting tracks in the presence of image noise similar in shape to tracks

Plastic track detectors never exposed to soil were etched and examined. The track density on these control samples was close to zero. Any real tracks would have to be from exposure to radon progeny at the manufacturing site. There were no significant findings on the control samples.

Plastic track detectors were also exposed to soil from Majuro for the same length of time as to soil from Rongelap. These exposures were used as a control to determine the number of tracks per unit area that resulted from natural or fallout radioactivity in uncontaminated Marshall Islands soil. In 111 field-of views (FOVS), the minimum, maximum, average and standard error of the mean were 0, 12, 3.6, 0.24 tracks, respectively. Therefore, on average, only about 3.6 tracks per FOV (at 10x) should be attributed to background radioactivity. Track densities (i.e. per FOV) in soil from Rongelap Island generally average several hundred.

Plastic defects, prior radon exposure and background radioactivity do not appear to be significant confounding factors in this study.

Track Counting

Counting of individual tracks and/or overlapping tracks in groups of up to about four individual tracks was accomplished rapidly in the FAST SCAN mode of the image analyzer. Track sizes reported in the data file greater than 3x to 4x the average track size can be interpreted to be overlapping tracks. The area is reported for each object in the "xxxx.hit" file." The size of objects can be used to estimate the likely number of tracks which formed it:

$$\# \text{ tracks per small object} = \frac{\text{area of object}}{\text{average area for single track}}$$

Counting of tracks within large groups of tracks or "clusters" is much more difficult and uncertain. All identified clusters can presently be inspected using the CLUSTER SCAN and the "xxxx.cls" data file or by manually moving the stage. Ultimately the number of tracks within each cluster will be counted explicitly. That process, however, will require further refinement and optimization of counting algorithms as the clusters exhibit a wide variety of image types which make counting very difficult. In particular, many clusters are dense masses of overlapping and hidden tracks. Preliminary analysis of clusters and total tracks is proceeding using a simple approximation of (cluster area)/(average track size) as a surrogate to track counts within the clusters. This approximation will always underestimate the true number of tracks in a cluster.

Three methods were developed here in an attempt to count tracks within clusters. All three methods are briefly described here as well as a "default" method and examples of images from each method are shown.

(1) Surface Focus Detection Method (SFD Method) - This could be considered to be the "default method" since it is the simplest, however, it is usually the least precise. The microscope is

focused on the surface of the plastic, the same as for counting individual tracks. The magnification is chosen for optimal resolution of the individual tracks and the image analyzer is allowed to count the individual tracks that it can recognize. The degree of success of this method depends on the proportion of the area of the cluster which is in focus, i.e., the proportion of the cluster area which is not composed of many overlapping tracks or which is not heavily damaged by the absorption of multiple alpha particles. See Figure 3.

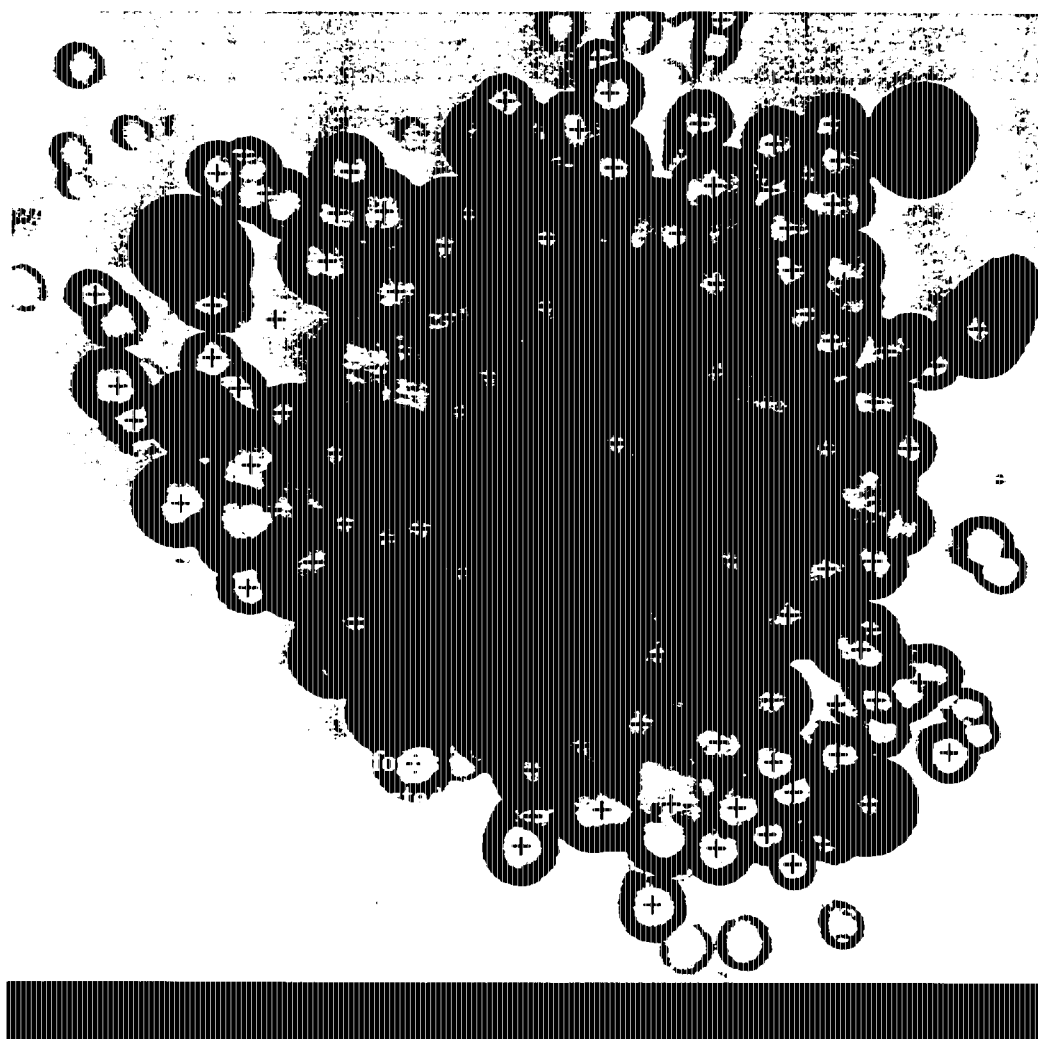
(2) Out-of-Focus Detection Method (OFD Method) - This method can work moderately well for clusters which include an area out of focus with respect to the surface, but which is not too heavily damaged within the area. The microscope is simply defocused to a point where "bright spots" are maintained for both the surface tracks and the partially focused deeper tracks. Finding an optimal focus point requires experimentation. The main criteria is the individual bright spots must be able to be distinguished by the "thresholding" algorithm of OPTIMAS. Thresholding is the process of discriminating objects from the background based on their brightness values (luminance). The "threshold" is one of several parameters than must be set by the analyst before scanning or counting. See Figure 4.

(3) MAX Detection Algorithm (MXD Method) - This method may work moderately well for clusters which have an area of deeper radiation damage than can be accommodated by the OFD method. This method first requires the analyst to image the plastic at two or more different depths of focus and save those images to memory buffers. Then, an arithmetic operation is performed which compares corresponding pixels in the two images and forms a composite made up the pixels of maximum brightness. All these operations are possible within OPTIMAS. The drawback is that there is some loss of sharpness to the overall image, however, it is relatively easy and fast to implement. See Figure 5.

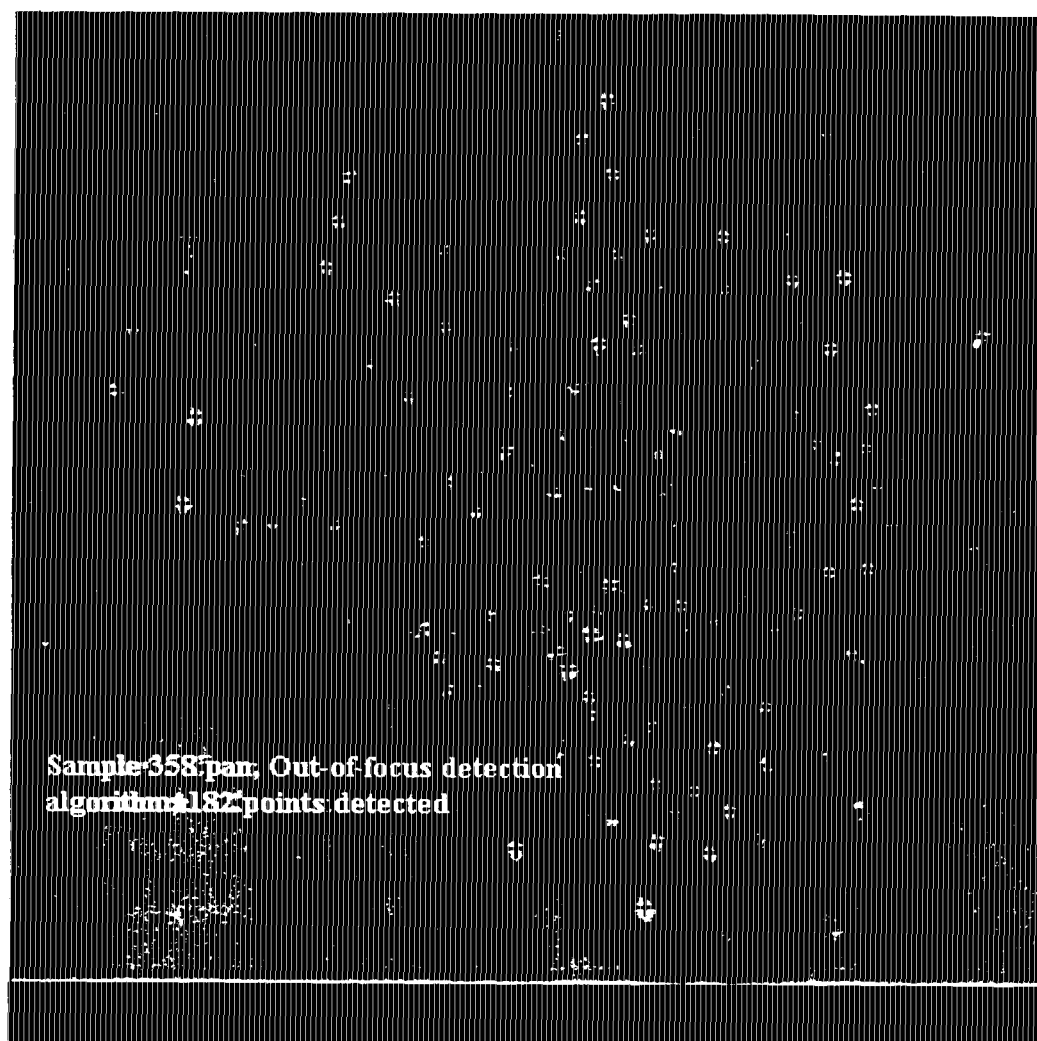
(4) Mask/Refocus Detection Method (MRD Method) - This method is similar in implementation to the MXD method. This method requires the analyst to first image the plastic at the surface. Then, using the mouse, an area is drawn on the screen encircling the out-of-focus or highly damaged area. This irregularly shaped region of interest (ROI) area will be used to define a "mask." The analyst saves the boundary points of the ROI to a buffer, refocuses to a deeper point in the image and pastes the mask onto the second image. The area of the second image that is within the mask is then saved to a second buffer. The microscope is refocused back to the surface; the image within the mask is pasted from the buffer onto the surface image forming a composite image of the two (or more) focal planes. See Figure 6.

The Need for a Cluster Counting Approximation

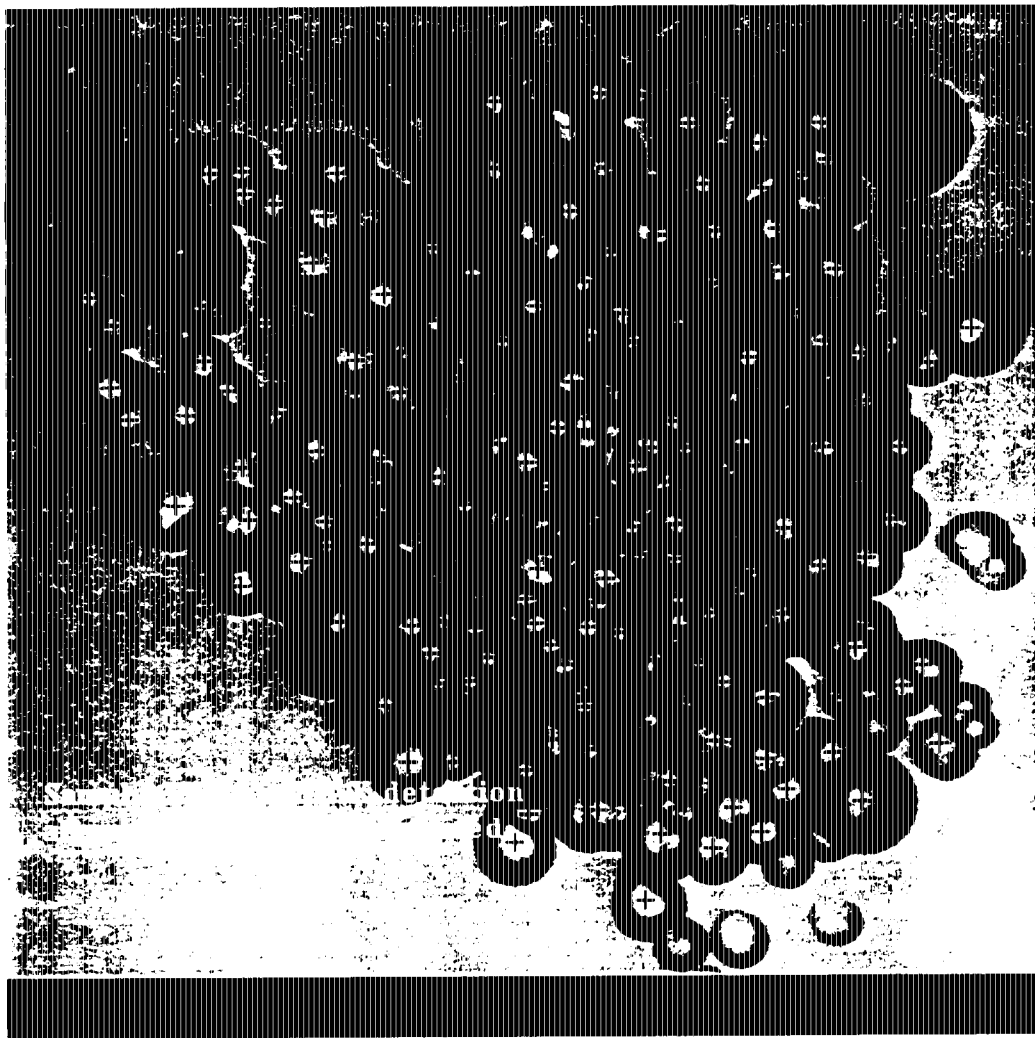
Preliminary investigation of possible methods for counting tracks within clusters has resulted in the determination that counting the visible tracks by any algorithm will reach a limit because



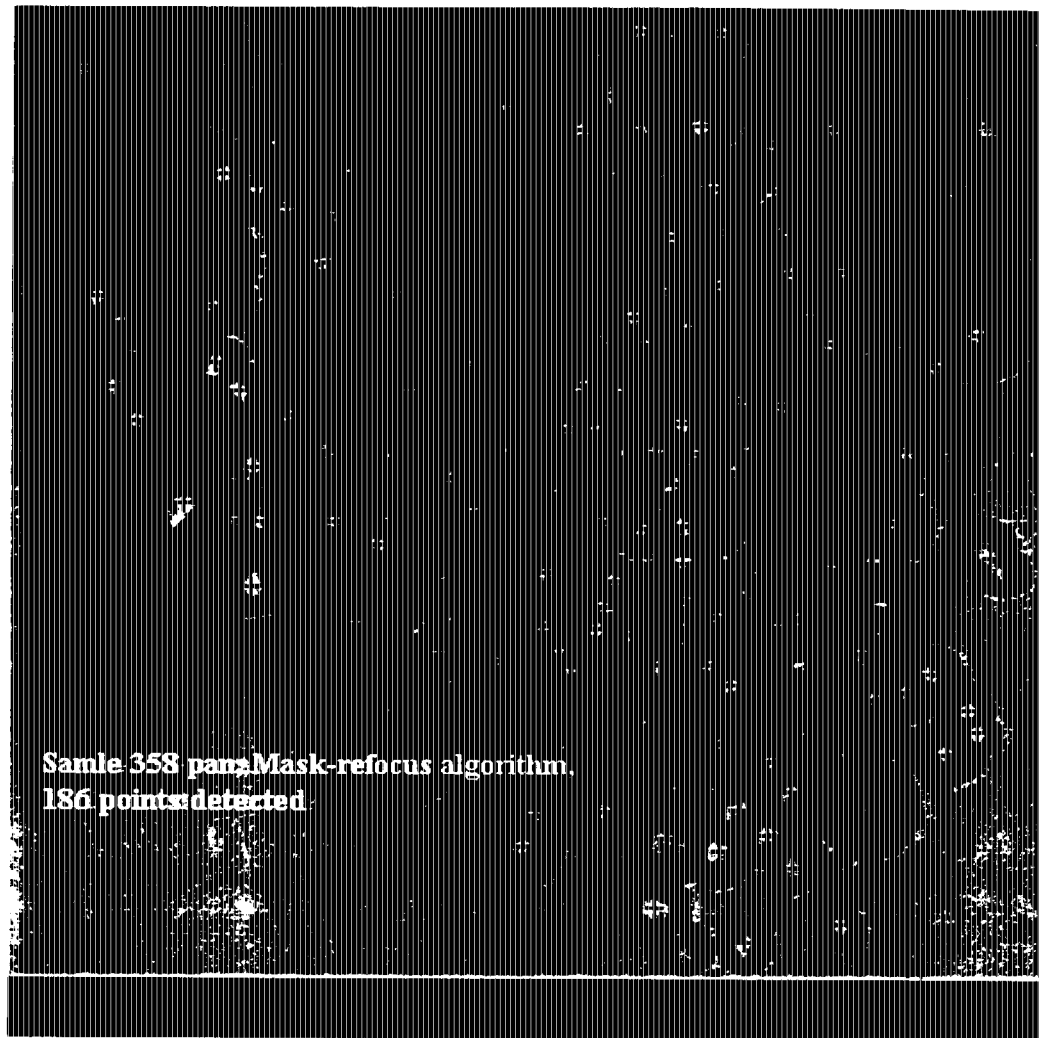
Example of 'surface-focus' detection algorithm



Example of 'out-of-focus' detection algorithm



Example of "MAX' detection algorithm



Example of 'mask-refocus' algorithm

only a limited number of tracks in a given area can be discriminated when overlap is significant. Examinations to date indicates that the relationship between cluster area and visible tracks (by any counting algorithm) never exceeds about 1.4 times the number of tracks estimated from the cluster area alone. Therefore, an important factor for determining the true number of tracks in a cluster is the percentage of tracks which are obscured by plastic damage and which cannot be successfully imaged. The number of obscured tracks is related to the size of the area of the cluster which is out-of-focus when the microscope is focused on the surface of the plastic. The obscured tracks are generally in the center of the cluster, at the point of greatest structural damage to the plastic.

Work is now in progress to measure the out-of-focus area and estimate the number of obscured tracks. The depth of the out-of-focus area can be determined directly from the micrometer scale on the fine focus knob and the capability for measuring the area of irregularly shaped regions of interest (ROI) already exists in the software. Thus, the final track count is likely to be computed from a total of three components: (1) the number of tracks in focus on the surface of the plastic, (2) the number of tracks in the out-of-focus area which can be counted by one of the three methods above, and (3) an estimate of the number of obscured tracks, this estimate being a function of the depth and area of the highly damaged section of each cluster.

Consultants

Mr. Scott Williams of Visioneering, Inc. (Las Cruces, NM) provided computer programming services. Dr. Russell Carey of Scientific Instruments, Inc. (Tempe, AZ) assisted the study in overseeing system development and providing advice on optical visualization technique. Mr. Terry Jenner of the Medical Research Council, Radiobiology Unit (Chilton, U.K.) visited the Majuro laboratory twice, once in 1993 and once in 1994 and assisted in track etching, track counting and experimental analysis.

Summary

The original objectives of this study were met to various degrees. The major accomplishments included the following. (1) An imaging computer/scanner was built for the purpose of inspecting alpha track patterns in CR-39 plastic which result from exposure to alpha emitters. The system can rapidly count individual tracks and determine the size and location of track clusters. (2) Alpha track patterns were produced from numerous soil samples from Rongelap Island. The images obtained in the course of this study show for the first time the microdistribution of alpha emitters in soil from Rongelap Island. The images show a variety of patterns; most include a rather uniform background of single tracks which result from very small radioactive particulates in the soil. In addition, there is a sparse dispersal of much larger conglomerates of atoms of alpha emitters. These small "hot particles" have been part of the main interest of this study and are further discussed in the accompanying publication. (3) Alpha track density as well as dispersal patterns were examined from soil which had been sieved into four different size fractions. More

tracks and more particles were observed in the smaller size fractions, indicating higher concentrations of alpha-emitters in the smallest size fractions. The two smallest fractions, 40-75 μm and $<40 \mu\text{m}$ were not significantly different in many samples. (4) Determination of the particle size distribution of the soil fraction less than 40 μm has been determined for a single sample at the Medical Research Council, Radiobiology Unit, Chilton, U.K..

A large number of track detector samples were exposed during the course of this study. Although the findings reported here are valid, they are representative of a small fraction of the samples available. Study of these samples is ongoing at the date of this writing. Measurement and interpretation of all the samples generated will likely require another year of study.

Reprinted here is a publication now in press on the initial findings from analysis of alpha tracks. The document as it is presented here has been peer reviewed and is now being published in the Journal of Radioanalytical and Nuclear Chemistry (1995). This document is a written version of a poster presentation made by Steven L. Simon at the Methods and Applications of Radioanalytical Chemistry - III Conference, Kona, HI, April 10-15, 1994.

Following the publication is a group of images of alpha track clusters from Rongelap soil for visual inspection.

Addendum to Study of plutonium microdistribution in soil

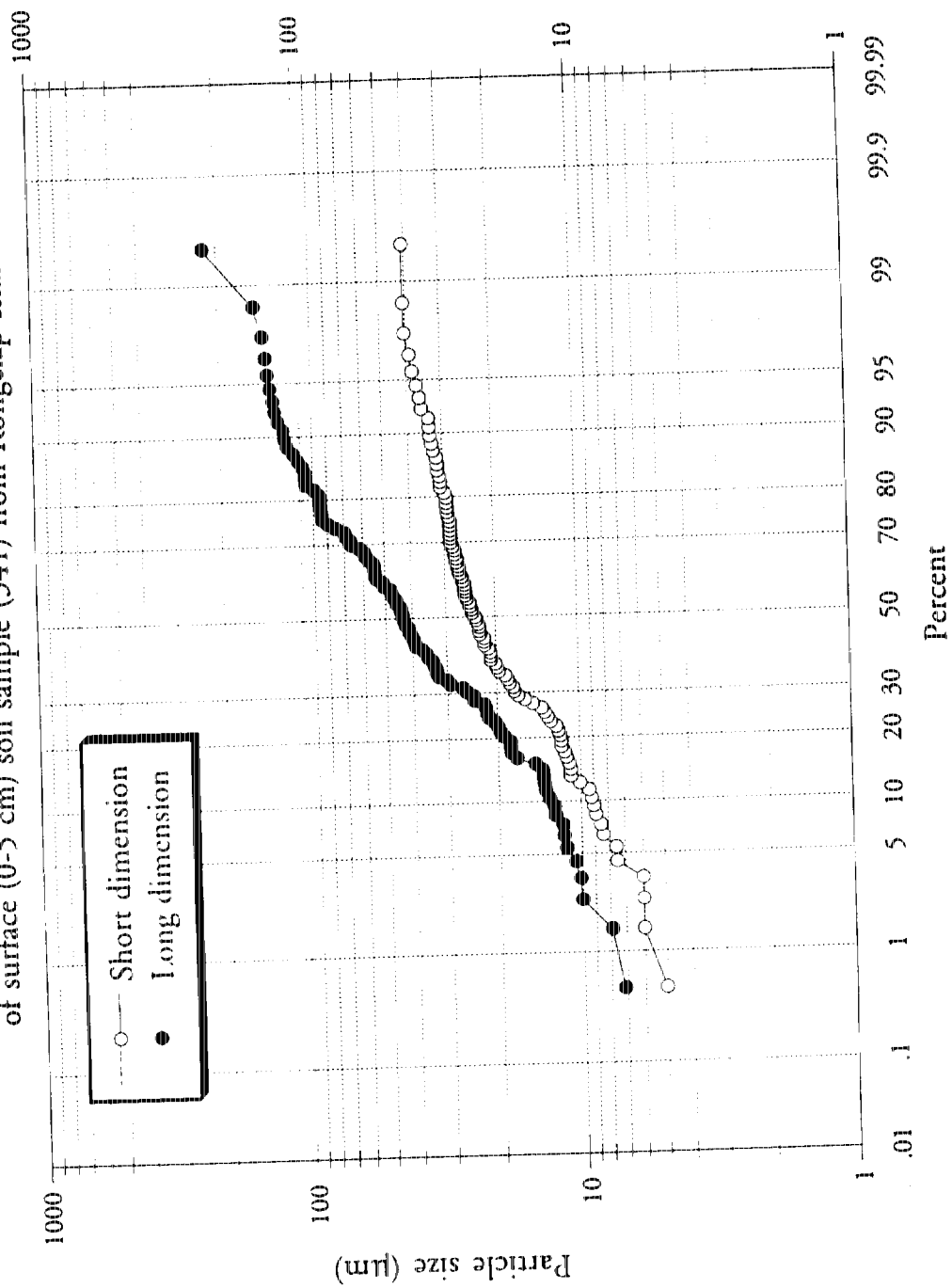
S. L. Simon and T. C. Jenner

3 April 1995

Enclosed are preliminary findings from a measurement of the particle size distribution of a soil sample from Rongelap Island. Soil sample 26S341 is a surface soil sample (0-5 cm depth) and was obtained from grid H2 on Rongelap Island. The sample was sieved in the RMI laboratory into 5 particle size fractions. The smallest fraction (0-40 μm size) was about 29% by mass of the entire sample. The smallest fraction was sent to Mr. Terry Jenner of the Medical Research Council, Didcot, U.K. for analysis. A confocal microscope was used to measure particle sizes. Preliminary data is presented here.

The particles were reported to be generally rectangular in nature. Measurements were made of the short and long dimension of 101 particles. The figure on the following page shows the probability distribution of the short and long dimension of each of the particles. The data for this single sample indicates that about 10% of the smallest fraction, and about 3% of the total sample, was less than 10 μm in size. Further study will be made on the relationship of particle sizes and plutonium activity.

Particle size distribution of <40 μm fraction
of surface (0-5 cm) soil sample (341) from Rongelap Island



A Comparison of Macro- and Microscopic Measurements of Plutonium in Contaminated Soil from the Republic of the Marshall Islands[†]

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Plutonium contaminated soil from the Republic of the Marshall Islands has been studied to determine the spatial and volume characteristics of contamination on two scales: (1) in macroscopic masses, i.e., gram sized samples, and (2) in microscopic masses, i.e., 10's of μ grams to 1 mg. Data on the homogeneity of transuranic radioactivity is presented for four different particle size fractions of soil. Three measures of volumetric homogeneity calculated from alpha track measurements on a plastic track detector (CR-39) are presented to quantitatively assess microspatial or microvolumetric variations. The nuclear track measurement data is contrasted with data obtained from conventional radiochemistry/alpha spectrometry.

The main interest of this study is a measure of the spatial or volumetric homogeneity of transuranic radioactivity in soil. The simplistic notion of mass concentration implicitly allows scaling of the mass concentration to units of various magnitudes: Bq/kg to Bq/g. The degree of homogeneity of the contaminants in the soil, however, becomes a limiting factor to the precision of such scale changes, particularly at small volumes or masses.

Spatial homo- or heterogeneity is, to some degree, a function of the relative proportions of radioactivity which is dispersed either as extremely small conglomerates of atoms or as larger aggregates of atoms, often called "hot particles." Understanding the size, frequency of occurrence, and spatial relationships of aggregates of radioactivity in surface soil is a primary, long term goal of this research. Because conventional radiochemical analysis techniques for alpha emitters do not provide information on microscales of measurement, nuclear track techniques are being investigated for suitability in providing supplementary information. This report provides preliminary data from a comparison of the two techniques.

The quantitative assessment of alpha-emitters in bone and tissue by the use of nuclear track techniques has been extensively reported. Only a few studies, however, have reported on the use of track measurement techniques to investigate the contamination of soil.¹⁻⁶ Some of these reports have discussed the potential for generating micromaps of the contamination; none have emphasized the quantitative assessment of spatial or volume variations.

Two scales of measurement are investigated here for analyzing soil samples: macrovolumes (or macro-masses) are considered to be on the order of a few grams to a few tens of grams while microvolumes (or micro-masses) are considered to be on the order of a few μ g (10^{-6} g) to about 1 mg.

[†] Presented at the Methods and Applications of Radioanalytical Chemistry - III Conference, Kona, HI, April 10-15, 1994.

The impetus for this study was the need for detailed information of the characteristics of transuranic contamination in the soil of islands which are being considered for rehabilitation in the Republic of the Marshall Islands. The Marshall Islands, site of the U.S. Atomic Weapons Testing Program in the Pacific from 1946 through 1958, is composed of 29 low-lying coral atolls. The atoll of Rongelap received significant radioactive fallout deposition 40 years ago in 1954. Studies are currently in progress to assess the risks from radioactivity in the environment of Rongelap Atoll. One issue of importance to future inhabitants is the level and characteristics of transuranic radioactivity in the soil. Normally transuranic radioactivity contributes only a small proportion of the total radiation dose to humans in these environments. However, inhalation dosimetric models are a function of particle size. Previously, no information on particle sizes of transuranics in the environment of Rongelap was available. The only radioactivity data was from measurements in bulk soil samples. Alpha track measurements can be used for quantitative studies of transuranic contamination of Marshall Islands soil because natural alpha emitters are in extremely low concentrations in soil on coral islands and, thus, do not interfere with such measurements.

Experimental

Study Design and Definitions: A comprehensive sampling and measurement program of transuranic radioactivity in soil is in progress for Rongelap Island. Most effort and expense has been dedicated towards the use of conventional radiochemical purification of the plutonium followed by measurement by alpha spectrometry. The weakness of this technique is that the radioactivity in a bulk soil sample is dissolved before measurement. Thus, all information is lost concerning the size and spatial distribution of radioactive particles. As part of an effort to focus on determining the degree of spatial homogeneity and distribution of particle sizes of the transuranic radioactivity in the soil, measurements of alpha tracks in plastic was added to our research program.

A plastic track detector, poly[ethylene glycol bis (allyl carbonate)], commonly known as CR-39[‡] was used to record the alpha tracks. Alpha track studies can generate large volumes of information when spatial information is recorded by a computerized image scanner. In this research, a computer controlled microscope was designed for the purpose of scanning CR-39 track detectors after their exposure to contaminated soil. The imaging computer records the number of single (i.e., non-overlapping) tracks in each Field-of-View (FOV) and their x-y locations. One measure of spatial homogeneity reported here is the variability of the "Number of Single Tracks/FOV." A FOV is typically 1.3 mm square (17X), a magnification at which single tracks can be easily identified and rapidly counted by an imaging computer.

The tracks in each FOV represent the recorded alpha emissions from about 17 µg of soil, equivalent to about 1 mg of soil for each cm² of CR-39 track detector. The calculation of the microvolume assumes an "effective thickness" of the soil, or range from which alpha particles can be emitted and still register as recognizable tracks in the plastic. The effective thickness of alpha particles from ^{239,240}Pu or ²⁴¹Am is approximately 10 µm.^{7,8}

[‡] Tastrak plastic track detector, manufactured by Track Analysis Systems Limited, Bristol, UK.

The alpha tracks which originate from dense and relatively large conglomerates of radioactive atoms are usually in the form of a cluster of tracks that cannot be optically resolved from one another. In some FOVs, a cluster of tracks (e.g., from a hot particle) will represent more radioactivity than from all the single tracks in that FOV.

Two other closely related measures of spatial homogeneity are reported here. The first, "Clusters per FOV", describes the spatial frequency of clusters. The second parameter, "Average % of Total Tracks from Clusters in FOVs with Clusters", describes the relative contribution of radioactivity from the clusters in those microvolumes containing "hot particles."

Finally, inspection of microscopic track images, though qualitative, is an effective way to quickly grasp the relative proportions of tracks that occur singly or in clusters; it is also an effective way to visualize the spatial variability of single tracks and of clusters. Some representative images are provided.

Soil Sampling and Preparation: Surface soil from 0-5 cm depth was extensively sampled on Rongelap Island on systematic grids with distances between samples ranging from 40 to 200 m. The purpose of that program is to study spatial variability on a scale important to the size of movements of people during typical daily activities. Those samples were measured for transuranic activity by conventional alpha spectrometry. The track measurements added a microscale measurement to assist in three areas of research: (1) characterizing the particle sizes of radioactivity for the purpose of refining inhalation dosimetry models. (2) developing probability distributions for soil ingestion calculations, and, (3) better characterization of soil contamination for the purpose of development of mitigation strategies.

Soil samples were split and both radiochemical extraction/alpha spectrometry and alpha track measurements were made. Sample preparation for both analyses included drying, thoroughly mixing, removing an aliquot of 100 g and sieving into four different particle size fractions: <40 μm , 40-75 μm , 75-150 μm , and 150-180 μm .

Macrovolume Measurement Technique: In this work, macrovolumes of soil were analyzed for mass concentration of plutonium by the technique of microprecipitation on neodymium fluoride.⁹⁻¹¹ Two grams of soil from four different size fractions were individually wet ashed in nitric acid to produce a uniform solution. From each solution, an aliquot of 0.1 to several g was extracted for chemical separation. The alpha particle emission from $^{239-240}\text{Pu}$ was determined by alpha spectrometry.

Americium-241 is also an alpha emitter and soil contaminant in the Rongelap soil. The concentration was determined by gamma spectrometry of the 59.5 keV emission using a high purity germanium detector. The sample size for gamma spectrometry of ^{241}Am in soil was normally 500 g. In terms of decays per unit time interval, the ratio of ^{241}Am activity to $^{239-240}\text{Pu}$ activity was approximately 1:1.6.

Microvolume Measurement Technique: The first step for the alpha track analysis was to immerse a 9 cm^2 piece of 1 mm thick CR-39 in contaminated dry soil in a cup for 44 d. Because both sides of the plastic are exposed, two different sets of alpha tracks are generated concurrently from each soil sample. Standard NaOH etching techniques for the CR-39 were used (6.25 N, 75°C, 4 to 6 h).

A computer-controlled microscope system was designed and built for the purpose of rapidly scanning areas of plastic track detector material, counting individual tracks and identifying the locations of possible clusters. Less emphasis was attached to making detailed measurements of each track. The image analysis system is PC-based and uses the Intel 80486 DX2™ chip operating at 50 MHz. Data acquisition is handled by a SHARP GPB-1™ image

processing board with a processing rate of 25 MHz or 40 ns/pixel. The interface for the analysis software is handled by Optimas™ software§ and uses custom written macro routines. An Olympus BHSM™ microscope with transmitted and reflected light modes was used for imaging tracks.

Alpha tracks are currently being imaged for automated counting in reflected light only. Reflected light allows tracks on either side of the plastic to be imaged with relatively little image interference from tracks on the other side. This is especially useful for our method of exposing both sides of the plastic to radioactively contaminated soil.

Scanning the track detector surface is accomplished by a computer controlled x-y positioning microscope stage. The plastic track detectors are raster scanned to cover the usable area, typically 1 to 3 cm². Generally, most scans are set up to include a minimum of 100 FOVs. A scanning rate of about 0.7 s/FOV was measured in simple benchmarking tests. Approximately 4 to 5 minutes is then required for the computer to sort several thousand records of track data. A computer file is generated containing the area and coordinate location of each track sorted by FOV. The track data is sorted by FOV so that the spatial variation can be easily explored.

In the scanning process, the computer driven microscope is first run in a "FAST SCAN" mode to count individual tracks, to store locations and sizes of individual tracks, and to save location data of objects which may be either clusters or artifacts. A "CLUSTER SCAN" is subsequently run using a binary file of location data which guides the microscope stage back to the location of the objects. During the "CLUSTER SCAN", the operator makes a visual determination as to whether the identified object is a true cluster or image noise (e.g., a scratch or speck of dirt) and "accepts" or "rejects" the object.

Counting of tracks within large groups of tracks or clusters is difficult and uncertain. Because the CR-39 in the center of clusters undergoes significant radiation damage, a precise count of the number of tracks in a dense cluster may not be possible. Preliminary analysis of track numbers in clusters proceeded using a simple approximation of (cluster area)/(average track area) as a surrogate to track counts within the clusters. This approximation will always underestimate the true number of tracks in a cluster.

Extensive counts performed on all individually identifiable tracks in dense clusters resulted in about 40% more tracks than the area approximation would predict. Subsequently, we adopted a value of 2x the number of tracks predicted by the area as an estimate of the true number of tracks. This approximation is used to account for the number of tracks obscured in the center of the cluster where the greatest structural damage occurs to the plastic.

Plastic track detectors were also exposed to soil from Majuro, the capital of the Marshall Islands and the location of the laboratory which conducted this study. Majuro is over 700 km from Rongelap, thus, the soil there has very low levels of contamination. The exposures to background soil were for the same length of time as the samples and were used as a control to determine the number of tracks per unit area that originate from uncontaminated Marshall Islands soil.

§ Bioscan, Inc. Edmonds, Washington.

Results and Discussion

Homogeneity Analysis: Data is reported here for four different samples obtained from locations 40 to 90 m apart on Rongelap Island. The samples were of near equal concentration as determined by macrovolume measurements: about 122 Bq/kg $^{239,240}\text{Pu}$ and 73 Bq/kg ^{241}Am . Table 1 gives summary data of the spatial homogeneity analysis determined from the Rongelap Island samples.

The concentration of transuranic radioactivity ($^{239,240}\text{Pu}$ plus ^{241}Am) in the four samples generally increased with decreasing particle size in macro-size samples (Table 1). The variation of concentration among the four samples decreased with decreasing particle size indicating greater similarity in the size fraction $< 40\ \mu\text{m}$.

The track analyses presented here are preliminary observations and only represent a first attempt at analysis of spatial information from alpha track measurements collected from areas of $1\ \text{cm}^2$ or larger. Results are reported here for each of the four soil particle size fractions previously noted. These results are not claimed to be representative of a larger population of samples. Because the data collected from even a few samples is extensive, these results are provided as examples for inspection and contrast.

The track measurements from uncontaminated Majuro soil provided the following findings: in 111 FOVs, the minimum, maximum, average and standard error of the mean were 0, 12, 3.6, and 0.24, respectively. Only about 3.6 tracks per FOV should be attributed to background radioactivity.

The "Number of Single Tracks/FOV" was lowest in the coarsest soil fraction (150-180 μm) and about 4x higher in the finer fractions. A similar trend was seen in the radiochemical analysis except the finer fractions had about 10x the concentration of the coarsest fraction. The "Number of Single Tracks/FOV" was nearly constant among the three size fractions 150 μm and smaller.

Somewhat different results were found in studies from the British Atomic Weapons Test Site at Maralinga, South Australia¹ where specific activities were noted to be greater in the soil size fractions $>90\ \mu\text{m}$. Presumably there are numerous factors that might influence the relationship of plutonium activity with soil particle size including the nature of the contaminating event, the degree of weathering since the contamination event, the chemical nature of the soil, and the particle size distribution of the soil.

In our measurements, alpha track clusters were most prevalent on the plastics exposed to soil of less than 150 μm size (Table 1). From 5 to 20% of the FOVs on the track detectors exposed to this particle size range may have clusters. The greatest frequency of clusters occurred in the fraction of 40-75 μm size. The frequency of occurrence, however, varies significantly from sample to sample, even for those samples obtained quite close together in the environment. The parameter, "Clusters per FOV", varied least among the four samples in the size fraction $< 40\ \mu\text{m}$.

In those FOVs (or related microvolumes) which show clusters of tracks, conglomerates of atoms (i.e., hot particles) are most likely a greater source of radioactive emission than the finely dispersed radioactivity which produces single tracks. Because the single tracks were generally constant among the three finest size soil fractions (see Table 1), the greater frequency of track clusters (i.e., hot particles) apparently accounts for the greater radioactivity in these fractions as measured by radiochemistry/alpha spectrometry.

Table 1
Summary of results of volumetric homogeneity analysis

	Sample No.	150 - 180 μm fraction	75 - 150 μm fraction	40 - 75 μm fraction	< 40 μm fraction
Number of Single Tracks/FOV	350	32.7	98.0	114	123
	353	27.4	103	78.5	77.0
	355	30.4	144	158	130
	356	15.7	73.3	116	99.2
	mean	26.5	105	116	107
	C.V. (%) ^a	28.5	28.1	27.9	22.6
Clusters per FOV	350	0.003	0.092	0.24	0.082
	353	0.011	0.041	0.10	0.087
	355	0.0	0.008	0.062	0.041
	356	0.0	0.034	0.058	0.030
	mean	0.00070	0.044	0.12	0.060
	C.V. (%)	57.1	69.6	64.4	41.4
Approximate % of Total Tracks from Clusters in FOVs with Clusters (n = no. of FOVs with clusters)	350	55 (n = 1)	66 (n = 29)	55 (n = 33)	52 (n = 15)
	353	81 (n = 2)	60 (n = 9)	60 (n = 17)	62 (n = 23)
	355	- (n = 0)	60 (n = 3)	53 (n = 22)	47 (n = 14)
	356	- (n = 0)	66 (n = 11)	50 (n = 13)	55 (n = 11)
	mean	68	63	55	54
	C.V. (%)	27.0	5.50	7.71	11.6
Pu + Am (Bq/g) ^b [% of total sample activity]	350	0.053 [15.7]	0.683 [19.3]	0.98 [9.2]	1.73 [16.3]
	353	0.115 [32.8]	0.571 [14.8]	0.65 [3.4]	1.34 [17.4]
	355	0.21 [41.0]	1.22 [18.3]	1.29 [6.5]	1.09 [10.9]
	356	0.065 [12.4]	0.457 [8.5]	0.66 [6.1]	1.05 [9.7]
	mean	0.11 [25.5]	0.73 [15.2]	0.90 [6.3]	1.30 [13.6]
	C.V. (%)	64.5 [53.8]	46.1 [32.2]	34.0 [37.9]	24.0 [28.1]

^a C.V. (%) = $100 \times \sigma/\text{mean}$

^b determined by radiochemistry/alpha spectrometry

In the microvolumes with hot particles, 50% or more of the radioactivity emission may come from the particles. The relative contribution of tracks from hot particles in those FOVs containing clusters remained remarkably constant (about 55 - 65%) among the four particle sizes fractions.

Some of the data summarized in Table 1 is shown in more detail in Figures 1 and 2. Each spatial homogeneity parameter formed a distribution of values among the FOVs. Generally, the "Number of Single Tracks/FOV" was normally distributed, though it tended towards a Poisson distribution for small track numbers. The distribution of the "% of Total Tracks from Clusters" was complex and could not be easily summarized. The chance occurrence of hot particles governs the resulting distribution.

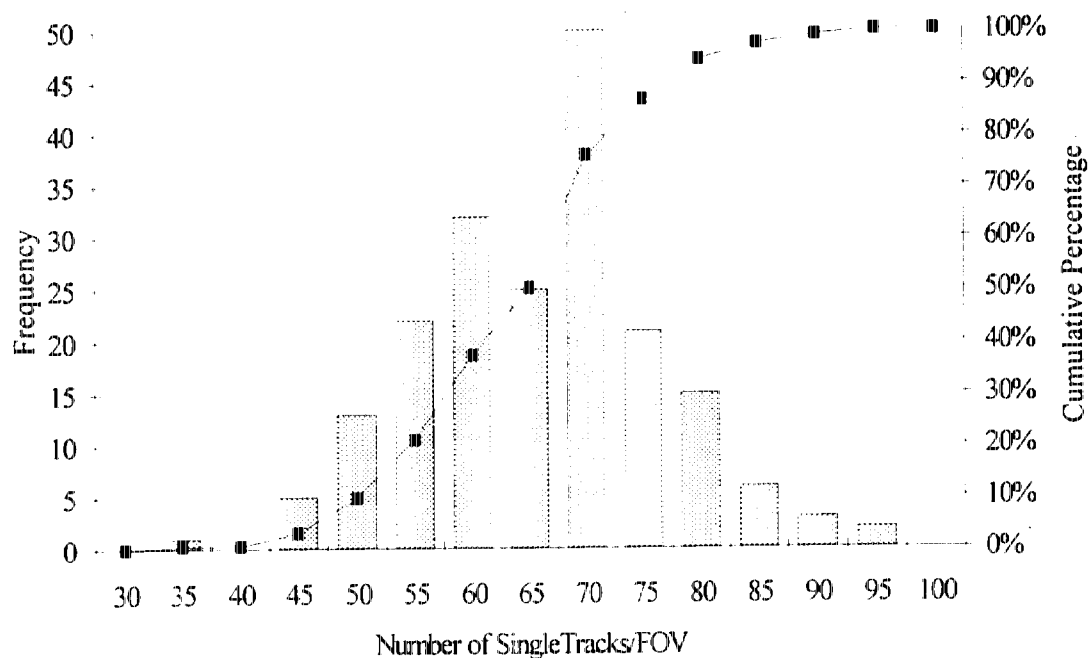


Fig. 1 Histogram of number of Number of Single Tracks/FOV in 195 fields ($1.7 \text{ mm}^2/\text{field}$); soil particle size $< 40 \mu\text{m}$ (Sample 350).

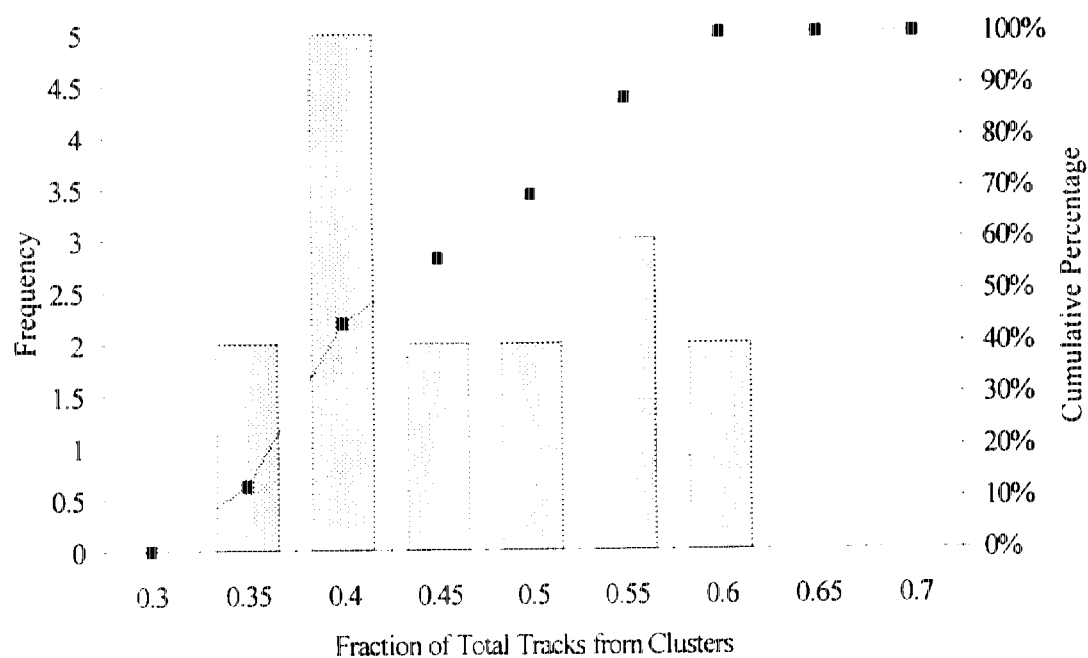


Fig. 2 Histogram of fraction of Total Tracks/FOV from Clusters. Data collected from 16 clusters in 15 FOVs; soil particle size $< 40 \mu\text{m}$ (Sample 350).

An important observation from this analysis is that most micro-volumes of soil do not have hot particles, consequently they have significantly less activity compared to those volumes with hot particles. This is, of course, an expected conclusion. The importance of this finding is that this is the first documentation of hot particles in this particular environment and the first quantitative assessment of the spatial frequency of such particles.

Figure 3 shows a representative image of a FOV containing a hot particle in the soil size fraction $< 40 \mu\text{m}$. Most striking is the relatively low density of tracks over most of the area as compared with that in the cluster.

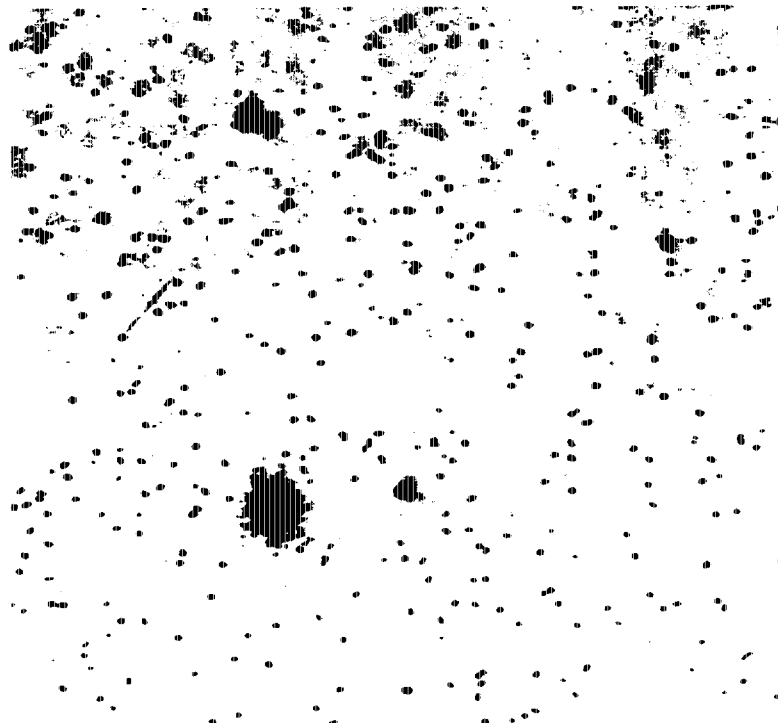
Comparison of Techniques: Conventional radiochemistry analytical technique and track analysis are complementary techniques. Radiochemical purification of transuranic radioactivity and measurement by alpha spectrometry is an accepted measurement technique and can be easily verified by independent measurements. It is most useful for analyzing bulk soil samples of several grams or greater. Unless such a soil sample is separated into particle size fractions before analysis, the data produced from such a measurement will not represent the true concentrations in the individual particle size fractions or in small volumes of the soil. Both the conventional radiochemistry technique and the track analysis indicate substantial concentration differences among the particle size fractions. Moreover, the track analysis indicates substantial heterogeneity between microvolumes.

Track measurements, in theory, can be quantitative and with proper calibrations could replace radiochemical/alpha spectrometric evaluation. After acquiring an image analysis system, cost per sample is significantly less. However, in practice, counting tracks in the presence of image noise and track clusters, not to mention natural alpha emitters, can be difficult. The greatest advantage of track measurement techniques in soil analysis is an assessment of micro-homogeneity by characterizing the size and spatial variation distributions of hot particles. In the samples from Rongelap Island, micro-heterogeneity was observed. This information is expected to be useful for specific types of dosimetric evaluations which are particle size dependent.

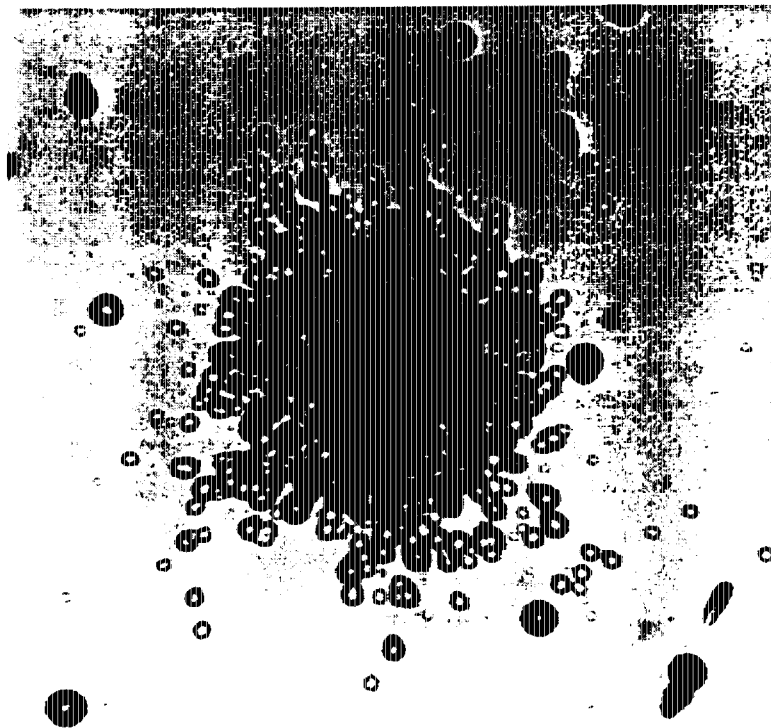
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Acknowledgments

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Field size is 1.3 mm x 1.3 mm.
Soil particle size is $<40\ \mu\text{m}$.

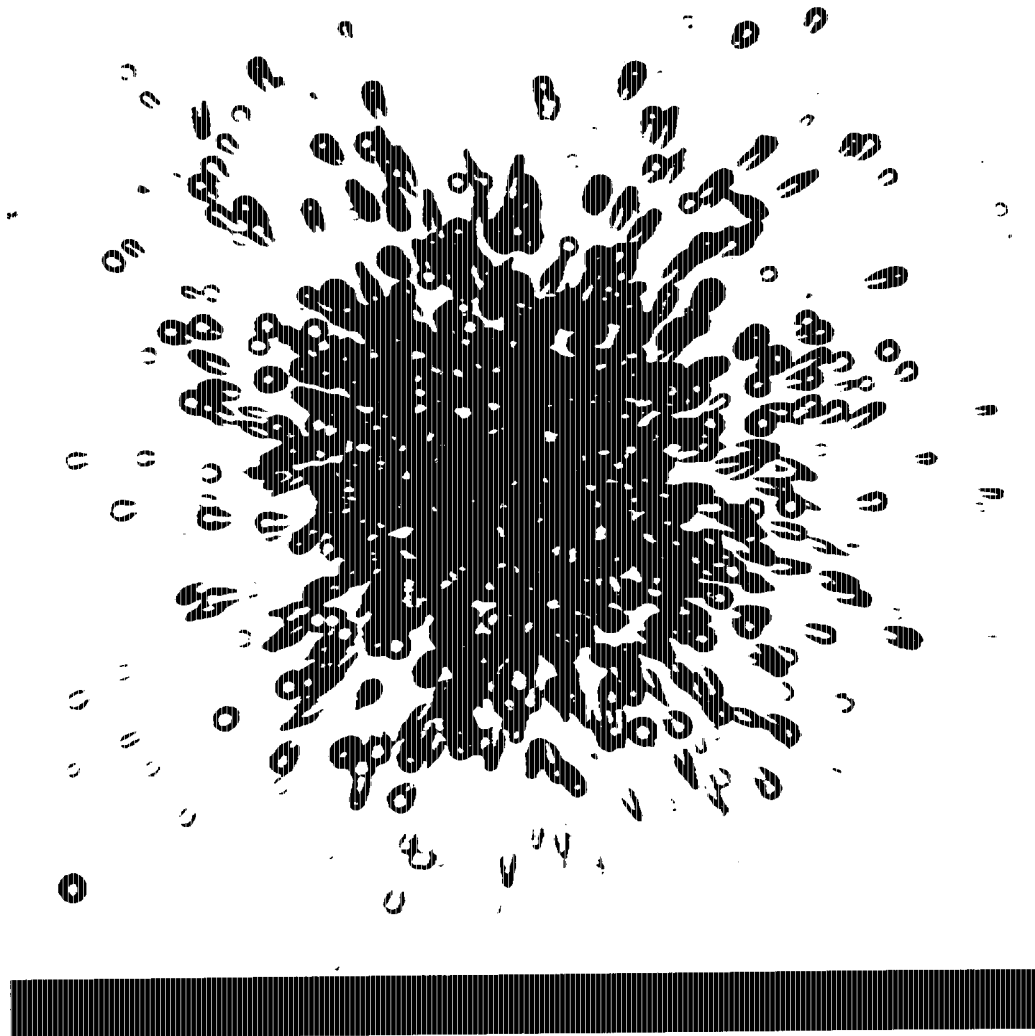


Field size is 217 mm x 217 mm.
Soil particle size is $<40\ \mu\text{m}$

Figure 3. Image of field-of-view showing single tracks and cluster (top), and magnified image of cluster (bottom).

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Example of 'star' type track cluster

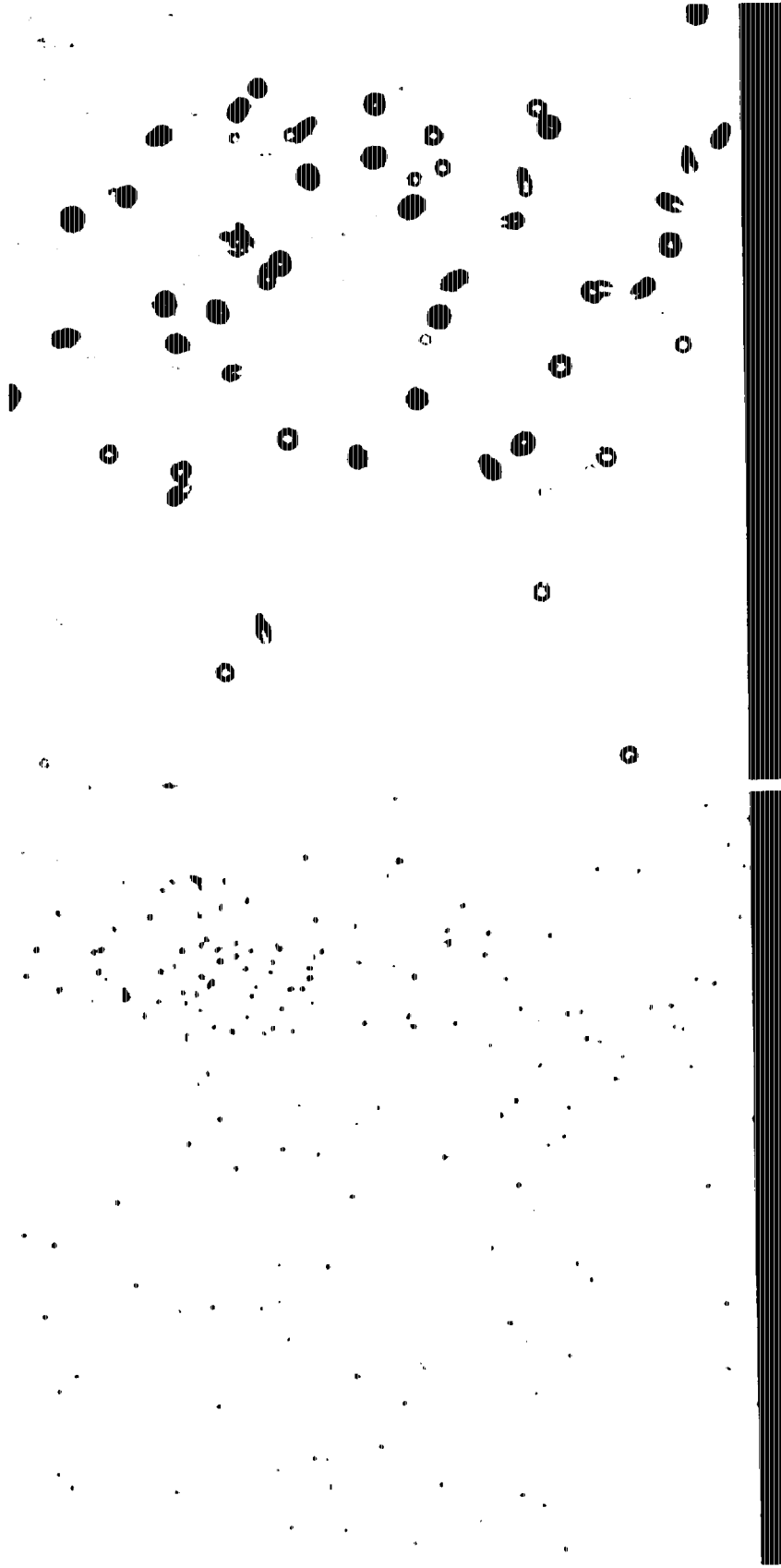


Image size is 1.3 x 1.3 mm.
Soil particle size is 150 - 180 μm .

Image size is 325 x 325 μm .
Soil particle size is 150 - 180 μm .

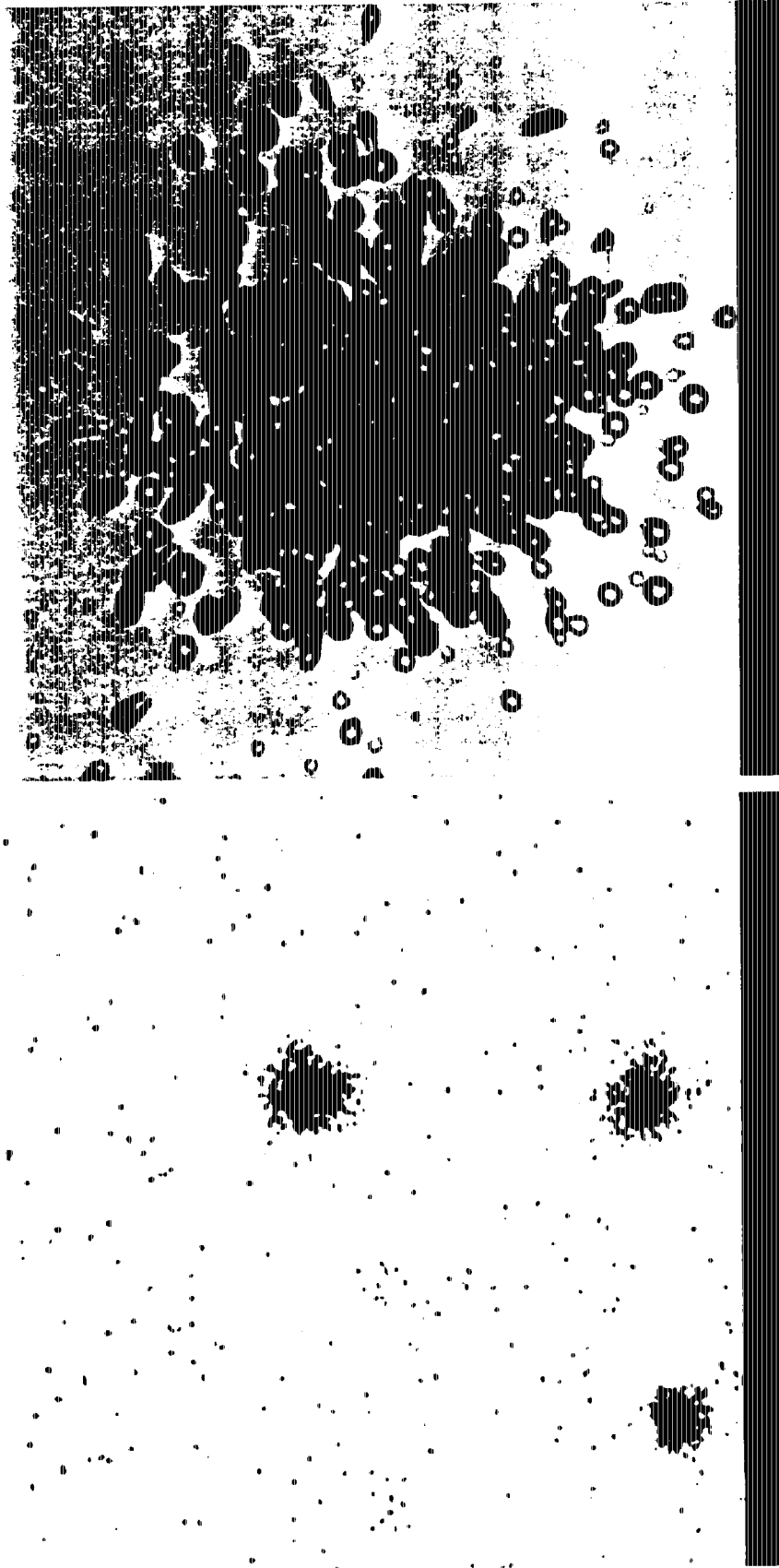


Image size is 1.3 mm x 1.3 mm.
Soil particle size is 75 - 150 μm .

Image size is 217 μm x 217 μm .
Soil particle size is 75 - 150 μm .

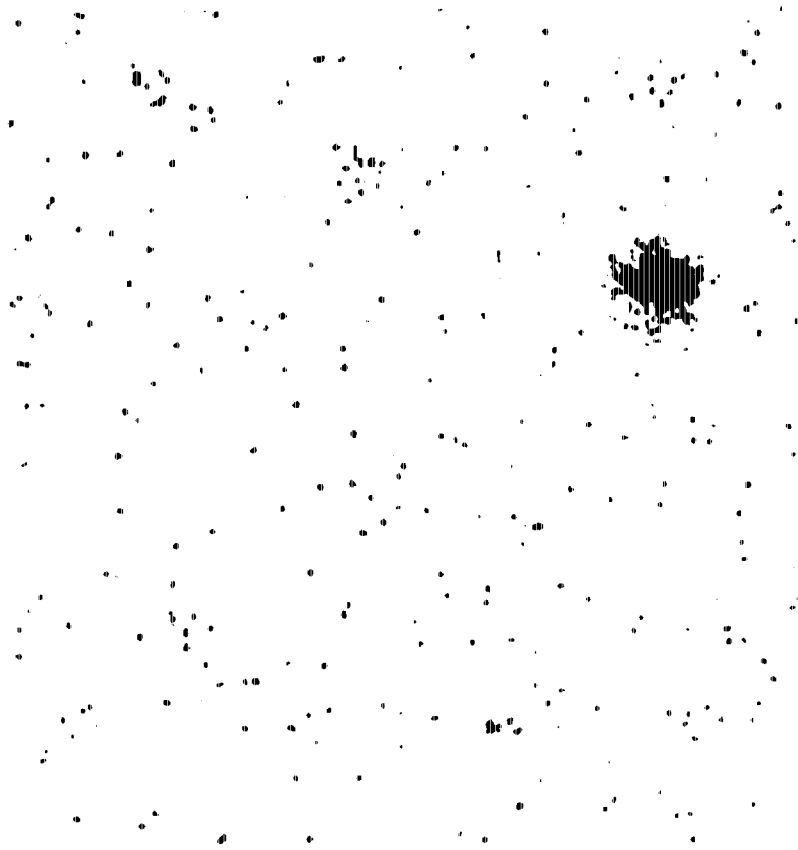


Image size is 1.3 x 1.3 mm.
Soil particle size is 40 - 75 μm .

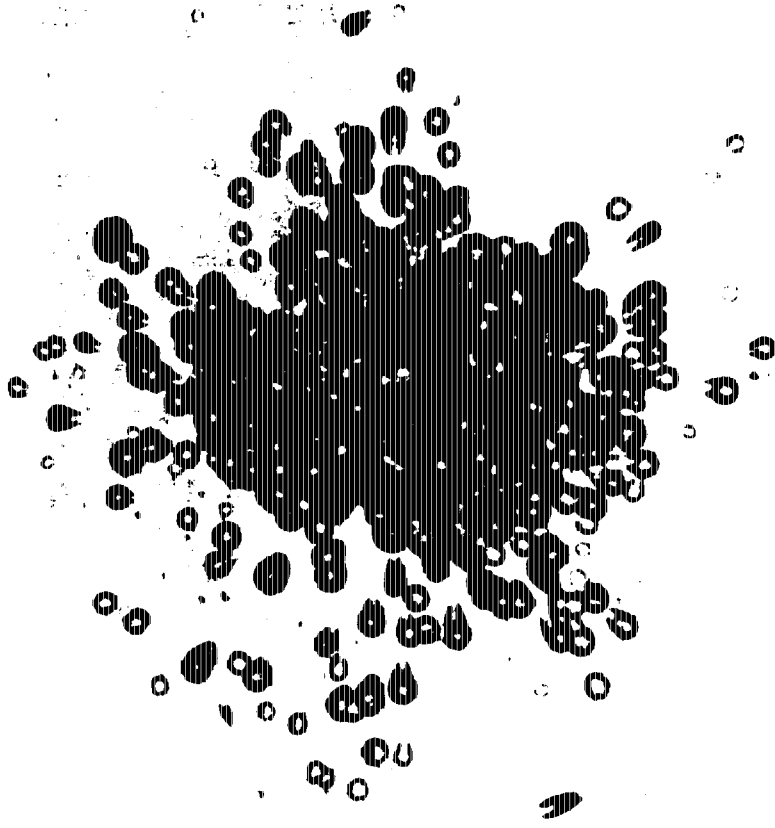
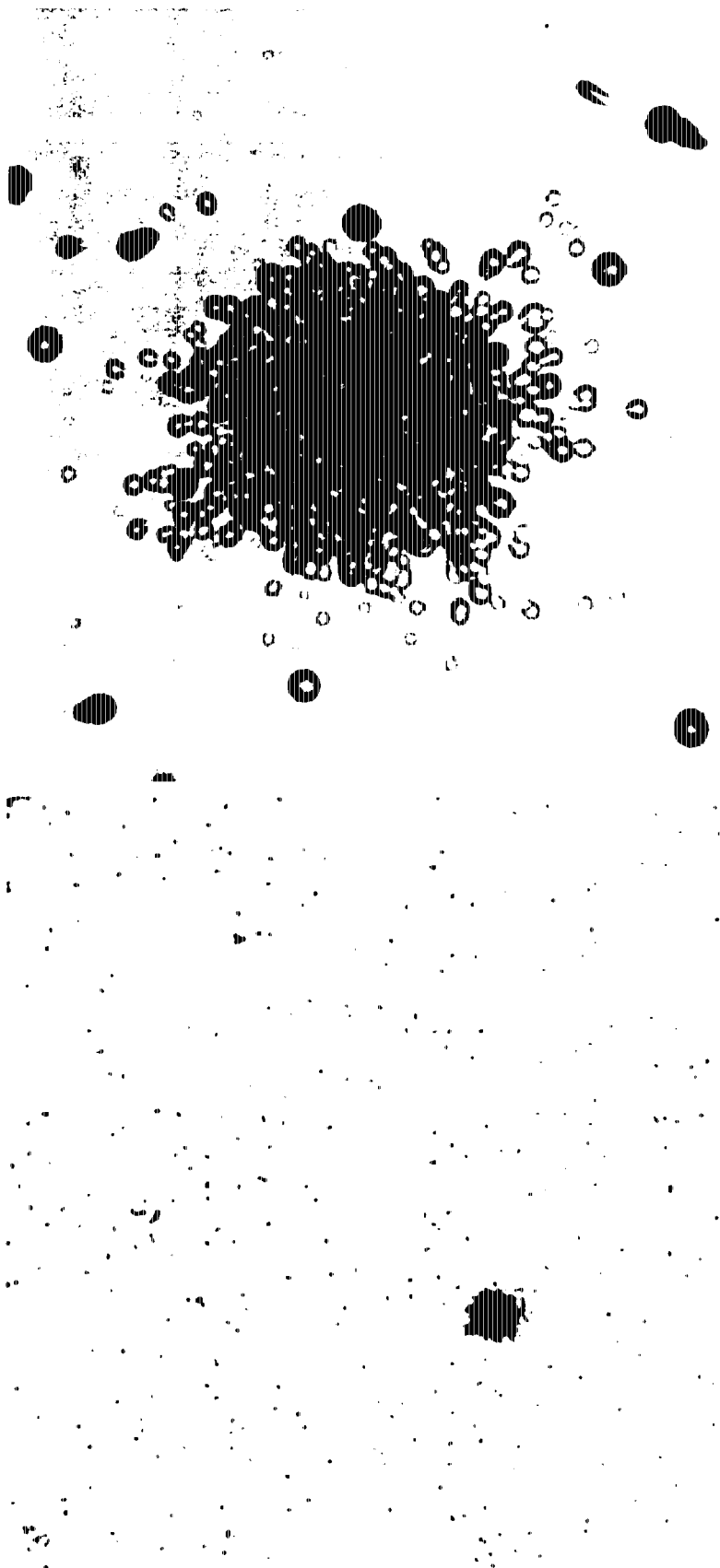


Image size is 217 x 217 μm .
Soil particle size is 40 - 75 μm .



Field size is 1.3 x 1.3 mm.
Soil particle size is <40 μm .

Field size is 217 x 217 μm .
Soil particle size is <40 μm .

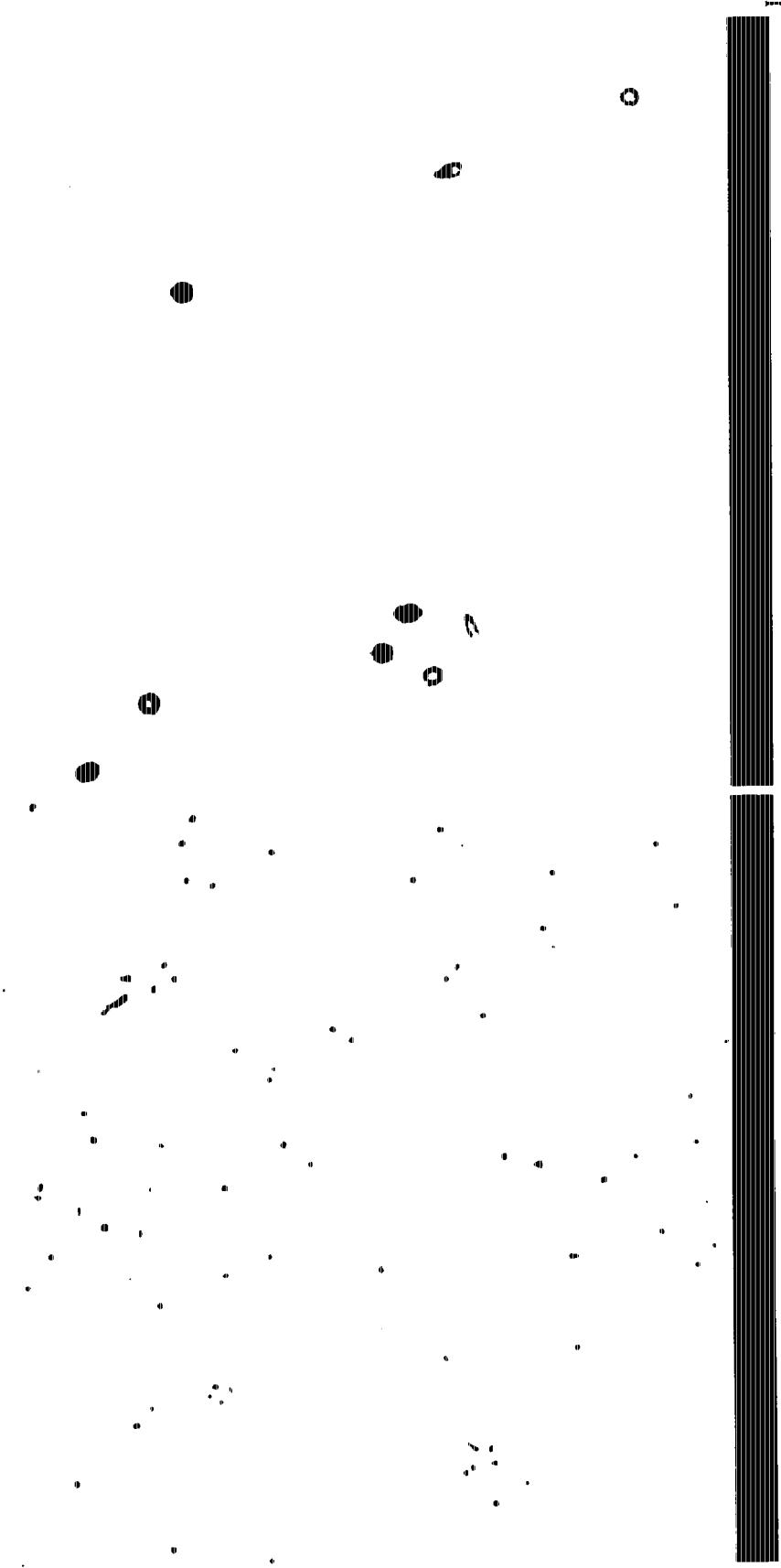


Image size is 1.3 mm x 1.3 mm.
Soil particle size is 150 - 180 μm.

Image size is 325 um x 325 μm.
Soil particle size is 150 - 180 μm.

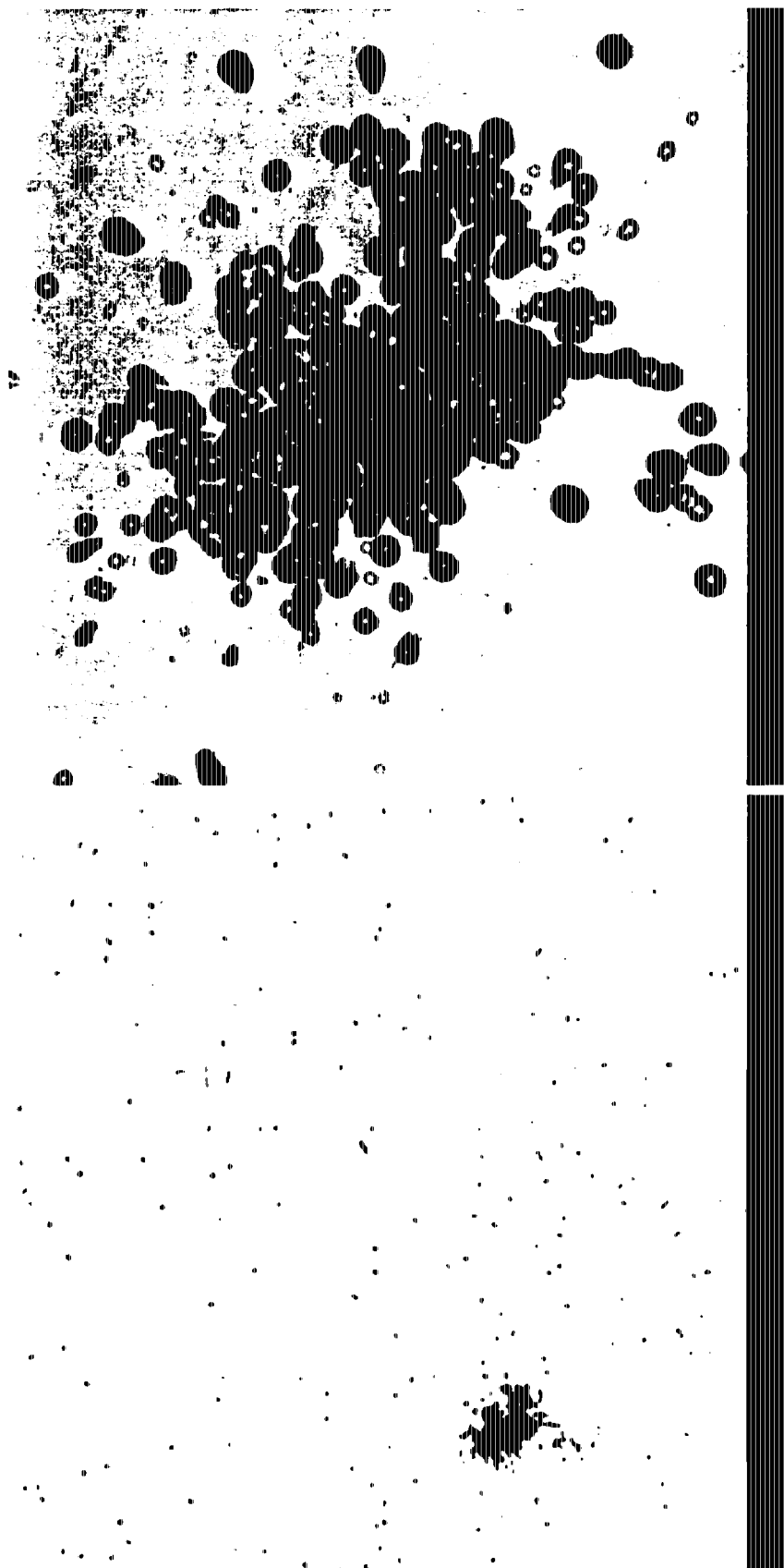


Image size is 1.3 mm x 1.3 mm.
Soil particle size is 75 - 150 μm .

Image size is 217 μm x 217 μm .
Soil particle size is 75 - 150 μm .

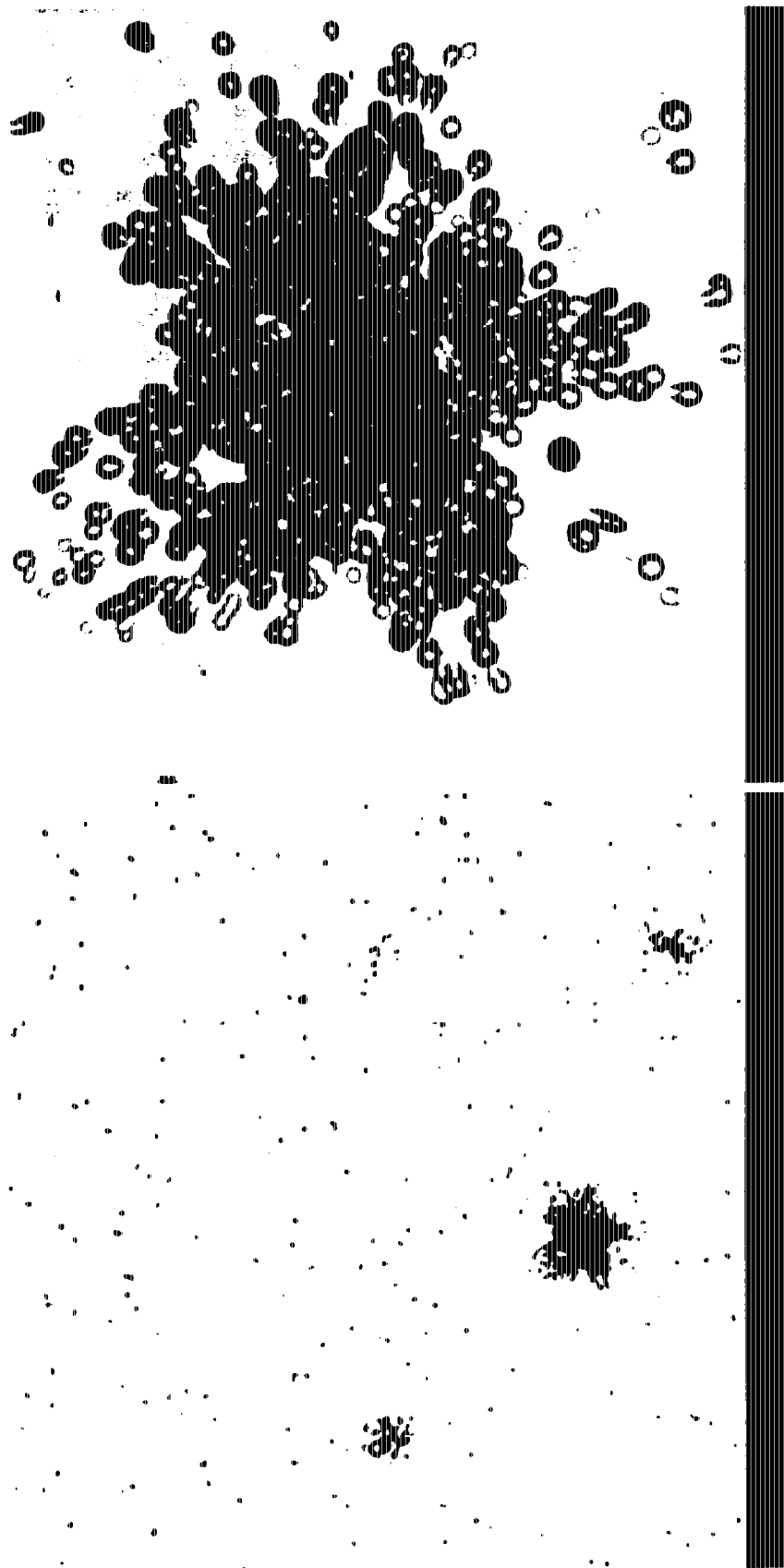


Image size is 1.3 x 1.3 mm.
Soil particle size is 40 - 75 μm .

Image size is 217 x 217 μm .
Soil particle size is 40 - 75 μm .

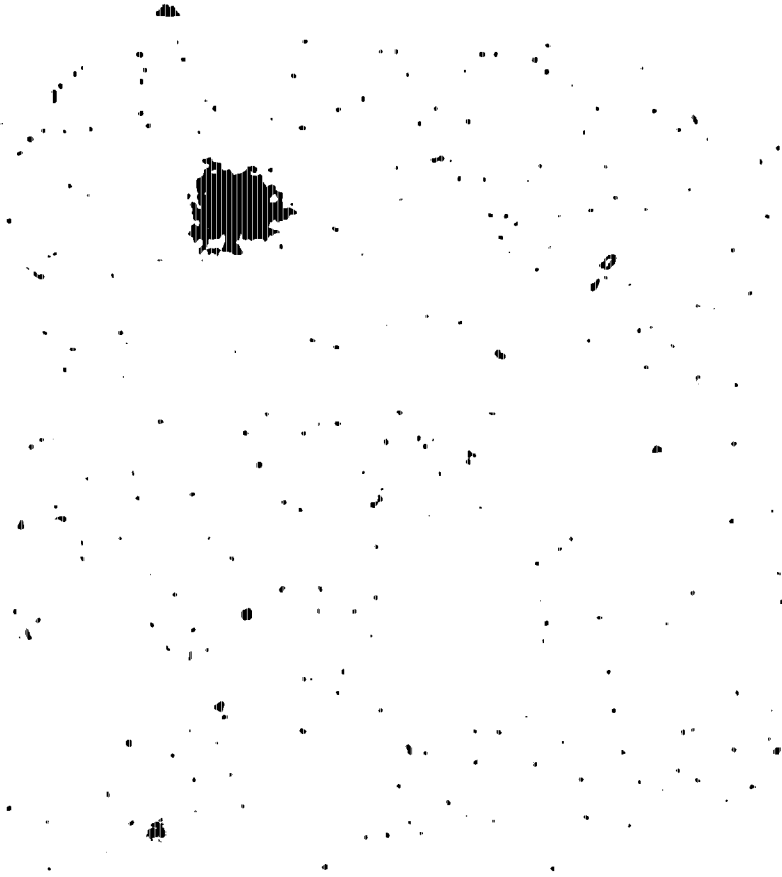


Image size is 1.3 mm x 1.3 mm.
Soil particle size is <40 μm .

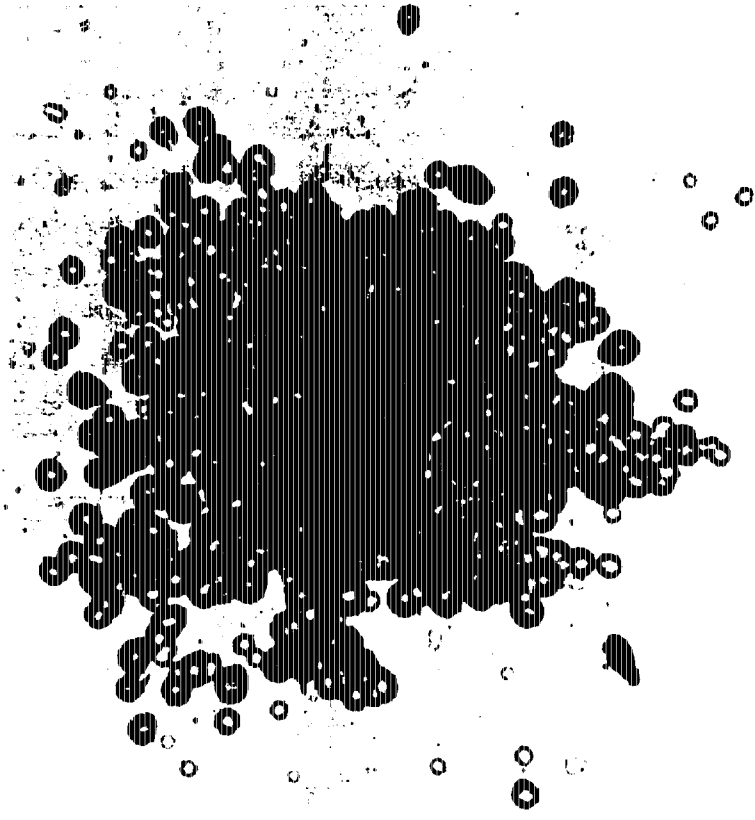


Image size is 217 μm x 217 μm .
Soil particle size is <40 μm .

APPENDIX A9

CHILD TRACE ELEMENT INTAKE STUDY (STUDY OF SOIL INGESTION):
A STATUS REPORT

S. L. Simon
RMI Nationwide Radiological Study

revised
October 1994

CHILD TRACE ELEMENT INTAKE STUDY (STUDY OF SOIL INGESTION): A STATUS REPORT

Steven L. Simon

BACKGROUND

The Rongelap Atoll Resettlement Project Work Plan is a set of scientific studies which seek to answer previously unanswered questions regarding the future safety of residing on Rongelap. The Rongelap community endorsed the possible resettlement of Rongelap Island provided two criteria could be met (RMI/RALGOV/DOE/DOI 1992): (1) The whole-body radiation dose to any one returning resident does not exceed 100 millirem per year (100 mrem/y) above natural background, based on a diet composed of food collected from only the southern islands of Rongelap Atoll, (2) the levels of plutonium and other transuranics on the southern islands of Rongelap Atoll must be shown by adequate monitoring not to exceed the U.S. EPA recommended screening level of 0.2 microcuries per square meter ($0.2 \mu\text{Ci}/\text{m}^2$), which may be translated into 17 picocuries per gram (17 pCi/g) or 629 Becquerel per kilogram (629 Bq/kg), if averaged over the top 5 centimeters of soil.

The issue of the contribution of plutonium and other transuranics to the total dose has to be reviewed in the light of data to be collected on how plutonium is spatially distributed in the soil, how much soil young children routinely ingest and the analysis of tissue samples from deceased Rongelap residents for plutonium burdens as a result of past exposure.

Ingestion of Soil as a Route of Potential Radiation Exposure

There are numerous pathways by which humans can receive radiation dose from radionuclides in the environment or by which their bodies can become contaminated with radionuclides present in the environment. It is well known that young children in particular are susceptible to intake of soil-borne substances whether it be pesticides, bacteria or radionuclides. During infant years, not only do children exhibit mouthing behavior whereby their hands are repeatedly moved in and out of their mouth during the day, but in unusual cases, young children (as well as adults) intentionally ingest soil. Both of these phenomenon are well documented in the literature and have been a public health concern because of the potential of young children to ingest lead from paints or fossil fuel contaminated soil. Based on preliminary calculations, the ingestion of plutonium which is resident in soil is not believed to be a significant hazard on Rongelap Island except under very unusual circumstances which would involve high ingestion rates. This study was originally motivated by the unanswered question about soil intake and the potential risk from plutonium ingestion.

Plutonium can expose man by only a few pathways. For example literature that indicates that plutonium and other transuranic radionuclides are not effectively taken up into plants via root

uptake. Therefore, food chain transport of transuranics to man via plants is not likely except possibly where unwashed plant parts are eaten. Soil can be deposited on plants as a result of resuspension or from direct contact with the soil during preparation. However, most species used for food in the Marshall Islands are peeled or cooked. Therefore, internal body contamination from plutonium in the soil is possible either as a result of inhalation or direct ingestion of soil and/or dust particles. Secondary sources will be from dirt that is dissolved in drinking water or soil adhering to fruits, vegetables, dried fish or other meats. In as much as the Rongelap Reassessment Project (Kohn 1989) identified that the dose to infants and small children is of continuing concern (p. 3) and because the Rongelap community continues to have concern about plutonium in the environment, a study was planned to determine the potential rate of intake of plutonium from soil among small children.

There are numerous estimates in the literature of soil intake rates, however, most estimates are based on weak assumptions, use little or no real data and are generic for typical westernized populations. Little information is available to characterize less well developed living situations such as that which might be found on outer islands. Calabrese et al. (1992) discussed the problem of the significant limitations of generalizing data to urban or non-caucasian children. Because of the noted world-wide prevalence of soil intake among young children and our lack of understanding of the degree of this phenomenon among Marshallese, this study was intended to determine representative intake rates which could be used to determine potential radiation risk.

The incremental dose from plutonium via soil ingestion study should not appreciably change the evaluation of compliance as set forth in the MOU. This argument, however, does not diminish the need to conduct the study. Because of uncertainties in evaluating internal dose and public concern, the evaluation of plutonium intake, particularly in children, should receive nearly the same degree of attention as total exposure to adults.

Basic Study Design

The Child Trace Element Study was intended to utilize methods which although are difficult to implement, have been successfully used by other researchers and have been reported in the literature (see for example, Binder et al. 1986; Clausen et al. 1987; Calabrese et al. 1989; Davis et al. 1990; van Wijnen et al. 1990). The methodology for estimating the possible intake of plutonium from the soil via ingestion uses trace element analysis of fecal samples to determine the time-averaged intake rate of soil. The potential rate of intake of plutonium, should the population return to Rongelap, can be estimated using the soil-intake rate and the plutonium soil concentrations reported in Appendix A6. There are several aspects of conducting a study in the Marshall Islands which are unique. In particular, sample procurement is somewhat more difficult because of the lack of controlled laboratory collection facilities.

The original design called for collecting fecal samples on board ship. This plan was later abandoned because of the high cost of ship rental and because it restricted the number of days during which fecal samples could be collected. The isolation of the subjects from soil during sample collection is important to prevent the stool samples from being contaminated by dust and/or dirt particles during collection.

REPORT ON ACTIVITIES COMPLETED

A significant effort during 1992 and 1993 went into developing a working and contractual relationship with the research group headed by Dr. Edward Calabrese of the School of Public Health of the University of Massachusetts (Amherst, MA). I personally visited there twice to meet with Dr. Calabrese and his staff and to provide introductory material to their group using video recorded on Mejjatto and Rongelap. Two representatives of the community, Mr. Aisen Tima and Ms. Abacca Anjain, accompanied me in February of 1992 to help brief the staff there and to answer their questions on issues important to the study.

Following is a brief outline of important steps taken to establish a collaborative relationship with the UMass group.

- November 1992 - I provided results of ICPMS trace element analysis of Mejjatto soil (analysis conducted in Scotland) to the UMass group. I received preliminary budget estimates from UMass for a 30 child study, 60 child study and 120 child study. Only the 30 child study did not exceed the total money available despite the original objective to include all resident children.

- December 1992 - I provided cost-cutting suggestions to UMass, suggesting in particular that individual food analysis, which is quite costly, could be reduced because of the limited dietary items available. I again provided the ICPMS analysis of soil to UMass. UMass suggests not to collect food at all but to analyze samples representative foods that I would provide. Through correspondence, UMass and I decided that as part of the protocol, we would repeat the collection of samples from children up to three times to improve the detectability of trace elements.

The original plan called for collection of fecal samples on board a ship to prevent direct soil contamination.

Plans were made for me to visit UMass early in 1993.

- February 1993 - Mr. Eisen Tima and Ms. Abacca Anjain of Rongelap and I visited UMass and met with staff there and the Vice Chancellor for Research. I requested a reduction in university overhead costs to reduce overall costs. UMass overhead was subsequently reduced from 52% to 26%.

UMass proposed a plan to conduct pilot study in which 5 volunteers ingested soil in a controlled study to determine recovery of trace elements. This was termed Phase I. Phase II was to include assessment of levels of trace elements in soil and food. Phase III was planned as the sample collection on Mejjatto. I provided further cost cutting suggestions and agreed to a timeline in which fecal samples would be collected by July 15 1993 (i.e., Phase III).

Eisen Tima, Abacca Anjain, Keith Baverstock and I traveled to Mejjatto to hold a community meeting concerning the plans to conduct the study. Soil samples were collected and a complete island house-to-house food inventory survey was conducted.

- Mid-March 1993 - Samples of fifty food items were obtained by the RMI radiation lab and were sent with soil to UMass for analysis.

- mid-April 1993 - Samples were delayed in transit for unknown reason and arrived in Amherst on 17 April 1993.

- May 1993 - UMass says that human subjects approval for pilot study should come within 10 to 14 days. UMass Contracts and Grants office notifies me that Calabrese has Principal Investigator status and would maintain all publication rights to study despite my indication that this was an unacceptable agreement.

- June 1993 - UMass writes and urges contract settlement so that supplies can be purchased. Lengthy phone discussions with their Contract department are held and some compromise language is decided upon. UMass personnel that were planning to come to the Marshall Islands do not have sufficient time for travel arrangements, etc. Randy Thomas from Mejjatto and I suggest to UMass that sample collection could be carried out by Marshallese staff hired at Mejjatto. The Rongelap Resettlement Project Administrative Group agrees to support me in the decision to reprogram money from the "Plutonium in Urine" Study to make additional funds available for the soil ingestion study. Keith Baverstock and Bernd Franke also agree to this. I communicate with UMass concerning the availability of more funding.

- late June to mid July 1993 - Communication with Calabrese at UMass is interrupted for unknown reason for over three weeks.

- mid- July 15 1993 - Sample collection trip is cancelled without notification. While in the U.S. working on the "Plutonium Microdistribution Study", I am able to reach Calabrese by phone. They request a contract from me while I am in the U.S. working on the "Plutonium Microdistribution Study". July 27, I write a revised contract and send by air courier to UMass.

- September 1993 - UMass writes and says that preliminary soil analysis indicates that tracer level may be too low to conduct study and will advise at later date. I write and ask for clarification. No response was received until February 1994,

- February 1994 - results of food sample analysis and soil analysis was received from UMass. They stated that "...a soil ingestion study based upon our earlier marker selection is not feasible."

Summary of Activities Completed

Because of the technical difficulties described, the Child Trace Element Intake Study was not completed. Thus, ingestion-rate estimates were not be realized. However, much background work and some measurements were completed. In particular, the following accomplishments were met:

- (1) Extensive literature review and literature summary was conducted. The literature summary has been submitted to a scientific journal for peer reviewed publication.

- (2) Two different sampling protocols were explored in detail for feasibility.

- (3) The spatial variability of trace elements in soil was studied on Mejjatto Island. The findings from mass spectrometry of 15 samples from Mejjatto are presented in Table A9.1.

- (4) In March of 1993, we conducted a food inventory survey on Mejjatto. This inventory was subsequently provided to the planners of the Mejjatto dietary survey (reported on in Appendix A4). The data from the food inventory survey was used to selected a group of thirty-three common foods which were subsequently analyzed by mass spectrometry for trace element content. These data are reported in Table A9.3.

(5) Analysis was completed to select optimal tracer elements based on highest availability in soil, lowest availability in foods, and low gut-to-blood transfer within the body. This analysis is presented in Table A9.4.

The following text presents the findings of work completed to date and discusses issues important to the eventual conduct of a soil ingestion study for the Rongelap community.

DESIGN DETAILS AND FINDINGS OF COMPLETED WORK

The original study was organized into the phases of: (1) Planning, (2) Training, (3) Sample Collection, (4) Sample Analysis, (5) Data Analysis and (6) Communication. Because of time and expense limitations and because of the remoteness of Mejjatto Island, a pilot field study was not planned. This was not viewed as a drawback because the sampling and analysis techniques have been proven in other studies previously reported.

(1) The Planning Phase included significant amounts of library research which necessitated visiting university libraries on the U.S. mainland. Publications, exceeding 200 in number, were collected on the topic of soil ingestion by humans. Phone contact was also made with several scientists experienced in urine and fecal sampling including Dr. Sue Binder at the Centers for Disease Control and Prevention who published one of the first quantitative studies on soil ingestion, Dr. Casper Sun of Brookhaven National Laboratory (BNL) who provided the BNL protocol for fecal sampling for bioassay including sample preparation instructions and cost estimates for bioassay collection kits, Dr. Scott Davis of the University of Washington (UW) who provided the UW protocol and sample collection instructions for a seven-day intake study and Dr. Edward Calabrese of the University of Massachusetts (UMass) who provided a 400+ page volume of recent publications describing methodologies for collecting soil ingestion data and for interpreting studies and their results. The review of acquired literature was useful for writing a comprehensive review of soil ingestion which has been submitted for refereed review and publication in an international scientific journal.

(2) The Training phase of the Child Trace Element Intake Study, though never implemented, was for the purpose of training women from the Rongelap community to function as staff to assist in the day-to-day sample collection and management of the subjects. Training was to be taught in a short workshop with selected women from the community who would then be hired to work as staff assistants in the study.

(3) The Data Collection phase of the study was planned to take several weeks to a months time. The original idea of collection of samples on-board ship was abandoned as discussed above. By revising the original plan, the sample collection period of each individual was extended from 2 days length to at least 5 days length. There are approximately 120 children on Mejjatto within the 1 to 8 year old age group who were expected to participate in the study. A repeat collection from about 20% of the subjects was planned for confirmation purposes:

(4) The Sample Analysis phase requires the use of a chemical laboratory such as the one in the laboratory of the Nationwide Radiological Study. Samples must be prepared for trace element analysis prior to mass spectrometry. The trace element analysis was planned to be conducted by inductively-coupled plasma mass spectrometry (ICPMS) (Lasztity et al. 1989; Wang et al. 1989). Various naturally occurring elements in the soil can adequately function as tracers and these are discussed in this document. Sample preparation would include freezing for temporary storage, drying and weighing, ashing (wet and/or dry) and sealing in plastic containers for shipment to an ICPMS laboratory for analysis.

(5) Data Analysis would be carried out by the Principal Investigator with collaboration with an outside statistician and would utilize accepted statistical methodology. The general objective is to determine the distribution of time-averaged soil ingestion rates among the 1 to 8 year old population and an estimate of the uncertainty associated with these values. In addition, analysis by sex and age will shed light on the critical groups.

(6) Communication with the Rongelap community was viewed as crucial for the success of the study. Community meetings were held and community members were involved in the planning stages, in collecting soil and food samples and in interviewing Mejjatto residents concerning the food inventory at the homes.

SPECIFIC STUDY OBJECTIVES

The primary objective is to understand the degree to which soil ingestion contributes to their overall dose commitment and risk, particularly among children returning to Rongelap. Transuranic radionuclides are of particular interest because soil ingestion is likely the primary pathway of concern for these elements. Soil ingestion-rate data was intended to be collected on every child of the Mejjatto population of the ages 1 to 8 years. In addition, the uncertainty of the ingestion rates should be estimated by some type of error analysis.

The distribution of ingestion rate values can be used to calculate the distribution of dose commitments expected among the returning population. That calculation would use also the spatial variation data of plutonium measured in samples from Rongelap.

Therefore, the results of a study would include:

- (i) distribution of soil ingestion rates,
- (ii) uncertainty estimates of individual rates and sex- and age-specific averages,
- (iii) distribution of dose estimates from intake of soil transuranic radionuclides via soil ingestion.

DEFINITION OF THE STUDY POPULATION AND LOCATION

All children of the Rongelap community between (and including) the ages of 1 to 8 years are eligible to participate in the study, however, the children must be present on Mejjatto during the time of the study to participate.

The present residence location of the Rongelap community on Mejjatto Island provides a suitable location to conduct the study. In particular, the living conditions, e.g., type of dwelling, cooking and washing facilities, etc. are not unlike that expected on Rongelap Island. Because the environment on Mejjatto is uncontaminated compared to Rongelap (preliminary measurements and estimates indicate there is only small traces of fallout radioactivity at levels consistent with worldwide background) the study may be accomplished without exposure of any child to plutonium as might be found on Rongelap. However, the relevance of conducting the study on Mejjatto for the purpose of extrapolating to Rongelap has been questioned. The degree of similarity between Mejjatto to Rongelap is an important question that must be considered. Because both islands are in the relatively dry, northern part of the Marshall Islands, the environments are indeed similar. The main difference which is important to this study is due to the larger size of Rongelap Island. The vegetation on Rongelap is thicker and the loam layer in the interior of that island is more highly developed. The loam soils of the interior of Rongelap Island are covered by thick grass and jungle-like growth and are not easily accessible for ingestion by youngsters under normal conditions.

In the future, the study could be conducted on Mejjatto, Rongelap or any of the northern islands.

DETERMINATION OF TRACE ELEMENT INTAKE, SOIL INGESTION-RATE AND POTENTIAL PLUTONIUM INGESTION-RATE

The soil intake rate can be estimated from empirical data of trace element intake as measured by fecal analysis. Trace element intake can be determined by analysis of fecal samples collected over a period of at least 48 hours. Longer collection periods, however, are preferable because intakes may be episodic in nature. Thus, longer sample collection periods (or observation times) are necessary to ensure that unusual intakes will be monitored.

It is well known that one's diet in part determine his or her trace element intake. It is mandatory, therefore, to monitor the diet for the purpose of determining the intake of the trace elements. An alternative is to furnish a diet of foods which minimize the trace element intake. The trace element intake which is known to come from dietary sources must be subtracted from the total intake to yield the trace element intake from soil sources.

The potential plutonium intake can be estimated as shown below,

$$\begin{aligned}
 & \left[\frac{\text{trace element amount excreted}}{\text{day}} - \frac{\text{food intake of trace element}}{\text{day}} \right] / \frac{\text{trace element content}}{\text{gram soil}} \\
 & = \frac{\text{grams soil eaten}}{\text{day}}
 \end{aligned}$$

The potential intake-rate of plutonium can then be estimated as:

$$\frac{\text{grams soil eaten}}{\text{day}} \times \frac{\text{plutonium activity}}{\text{gram of soil}} = \frac{\text{potential plutonium intake}}{\text{day}}$$

The method described above is a simplified formulation of a mass-balance approach to estimating soil intake rate (see Calabrese et al. 1989; Davis et al. 1990 for more information).

Candidate elements for trace element analysis are those elements which: (1) are present in the soil (preferably with low spatial variability) in substantial enough amounts that detection is likely possible, (2) have low gut absorption values, and (3) are uncommon in foods.

Trace element content of samples can be determined by various methods. The methods used by the most recent soil ingestion studies include wavelength dispersive x-ray fluorescence analysis (XRF, e.g., Davis et al. 1990), inductively coupled atomic emission spectrometry (ICP-AES, e.g., Binder et al. 1986) or ICPMS (e.g., Calabrese et al. 1989; Lasztity et al. 1989; Wang et al. 1989).

Table A9.1 below gives the findings from mass spectrometry analysis of surface soil sampled from Mejatto island.

Table A9.1 Concentrations of elements in soil from Mejjatto Island, Kwajalein Atoll, Republic of the Marshall Islands as determined by ICPMS (analysis performed by Department of Chemistry, University of Massachusetts, Amherst).

Analysis conducted on 15 surface soil samples (n=15). All measurements reported in µg/g unless noted as percent (%).

ELEMENT	Minimum	Maximum	Mean	Median	Standard Deviation*	Standard Error of the mean*
Li	0.10	0.10	0.10	0.10	0.00	0.00
Be	0.05	0.05	0.05	0.05	0.00	0.00
B	0.05	2.00	0.59	0.05	0.81	0.21
Na (%)	0.14	0.36	0.30	0.30	0.05	0.01
Mg (%)	0.93	1.59	1.19	1.11	0.20	0.05
Al	41.70	136.40	73.52	68.20	27.96	7.22
Si	170.00	320.00	226.67	220.00	44.19	11.41
Ca (%)	33.73	39.02	37.29	37.55	1.49	0.38
Sc	0.50	0.50	0.50	0.50	0.00	0.00
Ti	0.80	43.80	18.29	15.80	15.92	4.11
V	0.99	3.99	2.12	1.86	0.90	0.23
Cr	3.51	9.14	5.44	5.36	1.53	0.40
Mn	0.22	14.80	6.11	5.16	3.68	0.95
Fe(%)	0.00	0.11	0.02	0.02	0.03	0.01
Co	2.56	11.20	6.61	6.76	2.45	0.63
Ni	3.00	6.20	4.10	4.00	0.79	0.20
Cu	4.20	22.10	9.04	6.60	6.08	1.57
Zn	0.59	17.56	5.14	4.00	4.29	1.11
Ga	0.05	0.51	0.08	0.05	0.12	0.03
Ge	0.05	0.05	0.05	0.05	0.00	0.00
As	0.22	1.50	0.43	0.37	0.30	0.08
Se	0.10	2.34	0.77	0.10	0.83	0.21
Br	8.15	77.00	25.57	20.00	18.22	4.70
Rb	0.04	0.06	0.05	0.05	0.01	0.00
Sr (%)	0.43	0.59	0.49	0.50	0.05	0.01
Y	0.83	2.33	1.58	1.57	0.31	0.08
Zr	0.10	0.38	0.15	0.10	0.09	0.02
Nb	0.08	0.28	0.17	0.17	0.05	0.01
Mo	0.02	0.06	0.04	0.03	0.01	0.00
Ru	0.10	0.58	0.16	0.10	0.14	0.04
Rh	0.38	0.52	0.45	0.45	0.05	0.01
Pd	0.05	0.05	0.05	0.05	0.00	0.00
Ag	0.05	0.05	0.05	0.05	0.00	0.00

*elements with standard deviation, variance or standard error of the mean were at the instrument detection level (all values <MDC).

Table A9.1 continued.

ELEMENT	Minimum	Maximum	Mean	Median	Standard Deviation*	Standard Error of the mean*
Cd	0.02	0.09	0.03	0.02	0.02	0.01
In	0.05	0.05	0.05	0.05	0.00	0.00
Sn	0.68	4.32	1.48	0.95	1.03	0.27
Sb	0.02	0.16	0.04	0.02	0.04	0.01
Te	0.02	0.08	0.03	0.02	0.02	0.00
I	2.80	6.90	3.70	3.50	1.11	0.29
Cs	0.05	0.05	0.05	0.05	0.00	0.00
Ba	7.90	13.04	9.78	9.68	1.48	0.38
La	0.83	1.65	1.20	1.20	0.25	0.06
Ce	2.21	3.96	3.03	3.00	0.39	0.10
Pr	0.10	0.38	0.18	0.18	0.07	0.02
Nd	0.20	0.50	0.32	0.31	0.10	0.03
Sm	0.05	0.07	0.05	0.05	0.00	0.00
Eu	0.02	0.12	0.05	0.04	0.03	0.01
Gd	0.05	0.16	0.12	0.12	0.03	0.01
Tb	0.02	0.06	0.05	0.05	0.01	0.00
Dy	0.04	0.15	0.07	0.06	0.03	0.01
Ho	0.05	0.10	0.05	0.05	0.01	0.00
Er	0.05	0.13	0.06	0.05	0.02	0.01
Tm	0.05	0.05	0.05	0.05	0.00	0.00
Yb	0.05	0.11	0.07	0.06	0.02	0.01
Lu	0.03	0.05	0.05	0.05	0.01	0.00
Hf	0.10	0.16	0.10	0.10	0.02	0.00
Ta	0.10	0.10	0.10	0.10	0.00	0.00
W	1.78	17.60	8.70	7.08	5.47	1.41
Re	0.05	0.05	0.05	0.05	0.00	0.00
Os	0.05	0.05	0.05	0.05	0.00	0.00
Ir	0.10	0.10	0.10	0.10	0.00	0.00
Pt	0.10	0.10	0.10	0.10	0.00	0.00
Au	0.10	0.10	0.10	0.10	0.00	0.00
Hg	0.02	0.60	0.11	0.05	0.18	0.05
Tl	0.01	0.01	0.01	0.01	0.00	0.00
Pb	0.17	7.10	1.37	0.83	1.78	0.46
Bi	0.02	0.02	0.02	0.02	0.00	0.00
Th	0.06	0.34	0.13	0.10	0.07	0.02
U	1.49	4.07	3.15	3.05	0.69	0.18

*elements with standard deviation, variance or standard error of the mean were at the instrument detection level (all values <MDC).

Although titanium is widely used as a tracer for soil in various kinds of ecological and health studies, some degree of difficulty arises in its use with Marshall Islands soils. Because coral based soils are almost entirely composed of CaCO_3 , there is a significant amount of peak overlap on the ICPMS output from ^{40}Ca to $^{46,48,49}\text{Ti}$.

Comparisons of soil intake rates have been made in a number of recent studies using more than one trace element. In particular Binder et al. (1986) analyzed for Al, Si and Ti, Clausen et al. (1987) analyzed for Al and Ti, Davis et al. (1990) analyzed for Al, Si and Ti and Calabrese et al. (1989) analyzed for Ba, Mn, Si, Al, Ti, V, Y and Zr. In most of these instances, however, the different tracer elements led to unequal soil intake estimates. This anomaly has been attributed to excessively high ratios of the amount of tracer in foods to the amount in soil which is ingested (Calabrese et al. 1992). Calabrese et al. (1989) originally determined that Al, Si and Y were the most reliable tracers (lowest variability in recover), however, after more careful analysis, they reported that only Ti and Zr were recovered with acceptable limits of precision ($100\% \pm 20\%$ for 2 S.D.) (Calabrese et al. 1992). The potential source of interpretation error due to varying recovery of trace elements should be further evaluated as the review of literature progresses.

Table A9.2 below attempts to rank (from best to worst) soil trace elements in Marshall Islands soil based on soil content and having a low gut to blood transfer factor (termed f_1). A low f_1 factor ensures that the ingested trace element is not absorbed into the blood by transfer through the intestinal walls. Low gut transfer ensures that the tracer will be excreted in feces and can be used to accurately determine the amount of soil ingested. The elements appearing first on the list are the best candidates based on soil content and chemical characteristics alone.

Table A9.3 shows the results of measurements of a group of trace elements found in foods sampled from the Mejjatto community. The analysis and the selection of tracers was carried out by ICP-AES at the Department of Chemistry of the University of Massachusetts. As is known from the literature, toothpaste can contribute large amounts of titanium and aluminum to the diet and baking powder contributes aluminum. Smaller amounts of silicon are provided by baking powder, homemade dried fish, coconut juice and meat, and chewing gum.

Table A9.2 Elements in Marshall Islands soil ranked from smallest to largest f_1 (gut to blood transfer factor)¹ and secondarily by the amount of element transferred to feces. Lowest ranks indicate best candidates for fecal tracers based on soil content and chemical characteristics alone (availability in food not considered here).

Element	μg/g in soil	f_1	μg/g to blood	μg/g to feces	Rank
Y	1.58	1.00E-04	1.58E-04	1.58	1
Sc	0.50	1.00E-04	5.00E-05	0.50	2
Th	0.13	2.00E-04	2.50E-05	0.13	3
Ce	3.03	3.00E-04	9.10E-04	3.03	4
Nd	0.32	3.00E-04	9.58E-05	0.32	5
Pr	0.18	3.00E-04	5.31E-05	0.18	6
Gd	0.12	3.00E-04	3.54E-05	0.12	7
Yb	0.07	3.00E-04	2.13E-05	0.07	8
Dy	0.07	3.00E-04	2.03E-05	0.07	9
Er	0.06	3.00E-04	1.76E-05	0.06	10
Ho	0.05	3.00E-04	1.59E-05	0.05	11
Sm	0.05	3.00E-04	1.54E-05	0.05	12
Tm	0.05	3.00E-04	1.50E-05	0.05	13
Tb	0.05	3.00E-04	1.45E-05	0.05	14
Lu	0.05	3.00E-04	1.43E-05	0.05	15
La	1.20	1.00E-03	1.20E-03	1.19	16
Ta	0.10	1.00E-03	1.00E-04	0.10	17
Ga	0.08	1.00E-03	8.37E-05	0.08	18
Eu	0.05	1.00E-03	5.47E-05	0.05	19
U	3.15	2.00E-03	6.31E-03	3.15	20
Zr	0.15	2.00E-03	2.97E-04	0.15	21
Hf	0.10	2.00E-03	2.08E-04	0.10	22
Be	0.05	5.00E-03	2.50E-04	0.05	23
Pd	0.05	5.00E-03	2.50E-04	0.05	24
*Si	226.67	1.00E-02	2.27E+00	224.40	25
*Al	73.52	1.00E-02	7.35E-01	72.78	26
*Ti	18.29	1.00E-02	1.83E-01	18.11	27
Cr	5.44	1.00E-02	5.44E-02	5.38	28
V	2.12	1.00E-02	2.12E-02	2.10	29
Nb	0.17	1.00E-02	1.68E-03	0.17	30
Ir	0.10	1.00E-02	1.00E-03	0.10	31
Pt	0.10	1.00E-02	1.00E-03	0.10	32
Os	0.05	1.00E-02	5.00E-04	0.05	33
Sb	0.04	1.00E-02	3.93E-04	0.04	34
Sn	1.48	2.00E-02	2.95E-02	1.45	35

*elements measured in typical foods (see Table A9.3)

¹Eckerman, K. F., A. B. Wolbarst, A. C. B. Richardson. 1988. Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors For Inhalation, Submersion, and Ingestion. Federal Guidance Report No. 11, U.S. Environmental Protection Agency, EPA-5201/1-88-020.

Table A9.2 continued.

Element	µg/g in soil	f ₁	µg/g to blood	µg/g to feces	Rank
Hg	0.11	2.00E-02	2.21E-03	0.11	36
In	0.05	2.00E-02	1.00E-03	0.05	37
Co	6.61	5.00E-02	3.31E-01	6.28	38
Ni	4.10	5.00E-02	2.05E-01	3.90	39
Se	0.77	5.00E-02	3.83E-02	0.73	40
Rh	0.45	5.00E-02	2.23E-02	0.42	41
Ru	0.16	5.00E-02	7.77E-03	0.15	42
Ag	0.05	5.00E-02	2.50E-03	0.05	43
Mo	0.04	5.00E-02	1.87E-03	0.04	44
Cd	0.03	5.00E-02	1.62E-03	0.03	45
Bi	0.02	5.00E-02	1.00E-03	0.02	46
*Fe	236.40	1.00E-01	2.36E+01	212.76	47
*Ba	9.78	1.00E-01	9.78E-01	8.80	48
*Mn	6.11	1.00E-01	6.11E-01	5.50	49
Au	0.10	1.00E-01	1.00E-02	0.09	50
Pb	1.37	2.00E-01	2.75E-01	1.10	51
Te	0.03	2.00E-01	5.65E-03	0.02	52
*Ca	372873.33	3.00E-01	1.12E+05	261011.33	53
*Sr	4946.67	3.00E-01	1.48E+03	3462.67	54
W	8.70	3.00E-01	2.61E+00	6.09	55
*Mg	11873.33	5.00E-01	5.94E+03	5936.67	56
Cu	9.04	5.00E-01	4.52E+00	4.52	57
Zn	5.14	5.00E-01	2.57E+00	2.57	58
As	0.43	5.00E-01	2.17E-01	0.22	59
Re	0.05	8.00E-01	4.00E-02	0.01	60
Na	2966.67	1.00E+00	2.97E+03	0.00	61
Ge	0.05	1.00E+00	5.00E-02	0.00	62
Br	25.57	1.00E+00	2.56E+01	0.00	63
Rb	0.05	1.00E+00	4.93E-02	0.00	64
I	3.70	1.00E+00	3.70E+00	0.00	65
Cs	0.05	1.00E+00	5.00E-02	0.00	66
Tl	0.01	1.00E+00	1.00E-02	0.00	67

*elements measured in typical foods (see Table A9.3)

Table A9.3 Concentrations ($\mu\text{g/g}$) of trace elements in foods (tracers selected and analysis conducted by Department of Chemistry, University of Massachusetts, analysis by ICP-AES after fusion).

FOOD TYPE	Si ($\mu\text{g/g}$)	Fe ($\mu\text{g/g}$)	Sr ($\mu\text{g/g}$)	Ba ($\mu\text{g/g}$)	Mn ($\mu\text{g/g}$)	Mg ($\mu\text{g/g}$)	Ti ($\mu\text{g/g}$)	Ca ($\mu\text{g/g}$)	Al ($\mu\text{g/g}$)
baking powder	56.3	61.8	15.2	0.5	0.2	150	<1	19400	22956
baking flour	27.3	42.3	1.54	1.19	5.76	300	<1	240	7
canned fruit cocktail	10.2	2.42	0.9	0.5	1.38	73	<1	100	1
homemade cake	20.3	13.9	1.19	0.52	1.65	180	<1	640	664
homemade donut	13.3	21.68	1.12	0.78	2.84	190	<1	170	2.84
homemade pancake	13.1	19.33	1.91	0.82	7.8	200	<1	660	825
homemade dried fish	62.3	4.49	10.56	0.5	0.23	920	<1	1200	14.34
coconut juice/meat	49.7	2.64	7.78	0.5	4.14	1200	<1	980	1
coconut ewe	19.4	5.6	1.12	0.5	0.72	240	<1	220	1
commercial canned tuna	1.64	9.56	0.41	0.5	0.2	360	<1	50	1.4
canned corned beef hash	8.88	5	0.53	0.5	0.52	130	<1	160	0.56
canned spam	1.63	11.2	11.2	0.5	0.23	180	<1	150	1.95
canned mackrel	2.59	16.2	13.2	2.6	0.32	700	<1	1500	5.59
ramen noodles	23.4	41.8	1.55	1.03	4.82	220	<1	220	3.48
soy sauce	12.7	68.87	7.85	3.3	10.7	680	<1	220	3.56
USDA sliced carrots	7.71	11.03	7.51	1.69	1.44	78	<1	260	1
USDA canned chicken	10	5.27	0.5	0.5	0.2	190	<1	84	1
USDA evap milk	6.41	1.35	1.26	0.5	0.2	220	<1	720	1
USDA fruit cocktail	12.3	1.77	0.88	0.5	3.48	110	<1	120	1
USDA orange juice	2.2	1.95	1.52	0.5	0.2	82	<1	88	1
USDA peaches	22.2	26.47	6.77	0.5	4.52	120	<1	100	1
USDA rice	23.7	2.99	1.03	0.5	15.4	310	<1	60	1
USDA sweet potatoes	7.32	15.1	1.25	3.31	2.58	140	<1	140	1
USDA tuna	3.0	14.5	2.87	0.5	0.42	380	<1	250	1.99
solid shortening	0.43	1.56	0.63	0.5	0.2	5	<1	5	1
canned roast beef hash	17.4	4.96	0.79	0.5	0.79	200	<1	210	1.14
canned corned beef	8.14	17.2	1.18	0.5	0.2	120	<1	150	1
mayonnaise	0.16	0.88	0.77	0.5	0.2	7	<1	70	1
canned sardines	37.7	17.85	8.41	0.93	3.08	360	<1	2000	1.53
Tang™ Breakfast Drink	23.8	3.24	8.04	0.5	0.2	30	<1	1800	2.93
crackers	23.6	10.46	3.52	1.4	11.68	310	<1	210	4.9
toothpaste	74300	0.5	0.5	0.5	0.2	5	3266	5	1
chewing gum	260	23.9	4.88	0.5	0.77	130	4.1	1900	74.3

An optimal "tracer suppression" diet can be designed using the results of the ICPMS soil and food analysis. The diet should be suitable for a one complete week of intake (beginning 2 days before sample collection begins and continuing for five days while samples are collected). The diet should be developed in conjunction with dieticians resident in Majuro at the Ministry of Social Services. If a suitable low-tracer diet can be designed, collection of food samples from the study participants would not be required.

The choice of tracers can be determined by comparing the amount of tracer transferred to feces per gram of soil and per gram of food. The objective is to maximize the signal-to-noise ratio, where the "signal" is the tracer in feces from soil and the "noise" is the tracer in feces from foods. Several model diets should be evaluated this way. A simple comparison was made by equally weighting the foods analyzed in Table A9.3. The results of comparing tracer availability from soil and foods (see Table A9.4) indicate that Sr, Ca, Mg, Ti, Fe, Si, Ba and Mn are worthwhile candidates. The use of Ca would assume of course that dairy products were not included in the diet. Other elements not analyzed in foods are also excellent candidates. These would include Y, Sc, Th, Ce, La, U and other elements appearing at the top of the Table A9.2.

Table A9.4 Average trace element content in foods from Table A9.3 (disregarding toothpaste and chewing gum) and a ranking tracers based on ratio:

$$\frac{\text{amount of tracer per g of soil transferred to feces}}{\text{amount of tracer per g of food transferred to feces}}$$

All foods are weighted equally for simplicity.

Element	Average amount of tracer in food ($\mu\text{g/g}$) trans- ferred to feces	Tracer in soil ($\mu\text{g/g}$) trans- ferred to feces	(tracer transferred <u>from soil to feces</u>) (tracer transferred from food to feces)	Rank based on transfer to feces (Table A9.3)	Rank based on Column 4 of this table
Sr	2.78	3462.67	1246.82	27	1
Ca	726.58	261011.33	359.23	54	2
Mg	135.24	5936.67	43.90	49	3
Ti	0.99	18.11	18.29	53	4
Fe	13.45	212.76	15.82	26	5
Si	16.89	224.4	13.29	25	6
Ba	0.80	8.8	10.99	47	7
Mn	2.51	5.5	2.20	48	8
Al	782.81	72.78	0.09	56	9

SAMPLING AND ANALYSIS PROTOCOLS

The entire population of children from 1 to 8 years of age should participate in such a study. Intentional soil intake is likely a rare phenomena and a high level of participation will ensure a higher probability of detecting occurrences in the population.

The families should not be notified until the day of participation to hopefully prevent any unnatural behavior prior to the sample collection period.

Depending on budgetary constraints, the individual stool samples from each child could be analyzed separately. This kind of analysis would enable the time-dependence of excretion for each child to be observed as well as the variation of the time-dependence among children. To calculate the total intake by a child over a defined period of time, the total excretion (minus any food contributions) would be summed or a pooled fecal sample could be analyzed.

Also depending on budgetary constraints, a repeat collection of a subset of the children should be considered, e.g., a randomly chosen group of 15 - 20%. Repeat collections would provide confirmation that the samples obtained from specific children were representative of the soil eating behavior of that child.

RECORD KEEPING

Sample collection record keeping sheets must be provided in both English and Kajin Majol (Marshalllese) and must be fully explained in the training sessions.

In addition to gender and age, data should be collected on general health status of the children. This could be facilitated by a staff nurse. Unusual behaviors or health conditions should be noted.

The date and time of collection of each sample should be recorded as well as the sample wet weight. Notes should be kept if a sample was missed for any reason or if a portion was lost.

CONFIDENTIALITY

Confidentiality of the results for individuals should be maintained as is generally accepted practice in health studies. However, the results will be available to the family of each subject. A master index of names and identification numbers will be maintained in the permanent records of the study, however, all data analysis will utilize only an identifying number for each subject to maintain anonymity.

OVERSIGHT

An international oversight group should have the responsibility of reviewing sampling designs, protocols, data analysis and results and conclusions. Such a group would have the option of soliciting outside consultation in technical areas not represented by their respective areas of expertise.

SUMMARY

The most important aspects of the study as planned are noted here.

(1) Stool sample collection from the entire population of 1 through 8 year old children - ensures that unusual behaviors in the population are likely observed.

(2) Control of sample contamination is possible by utilizing local assistants and adequate training program.

(3) Design and control of diet - designing a low tracer diet is possible and minimizes the confounding intake of tracer elements through food as well as reducing the costs of individual food analyses.

(4) Measurement of a suite of trace elements - improves the overall analysis capabilities, analysis can be explored using individual elements or by ratios of elements, etc.

(5) Study can be used to estimate potential plutonium intake without actual exposure of children or community members to plutonium.

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APPENDIX A10

VERIFICATION OF THE MEASUREMENT OF PLUTONIUM IN URINE: A STATUS REPORT

S. L. Simon
RMI Nationwide Radiological Study

1994
Revised January 1995

INTRODUCTION

One of the studies contemplated in the original workplan for the Rongelap Resettlement Project was to verify reported measurements of plutonium in urine of Rongelap community members. The impetus for this work was to provide assurance to the community of the precision of this data and to provide interpretation of the values. The intent of this study was to have measurements conducted which would confirm or verify the measurement data reported by Brookhaven National Laboratory. Because no other technique currently rivals the sensitivity of fission track analysis, it was realized that some compromise in performing a comparison would be necessary.

The best available technique was viewed to be inductively-coupled plasma mass spectrometry (ICPMS), however, no laboratories could be identified with experience in measurement of heavy ions at the required level of sensitivity except current Department of Energy contractors (in particular, Battelle Pacific Northwest Laboratories). Moreover, the data acquired by study of transuranics in bones of deceased former residents of Rongelap Atoll (see Appendix A7) could, in part, replace the need for urine measurements of plutonium.

This study was viewed with a lower priority than the other studies because they sought new information, whereas this study was only intended for confirmation purposes. In June of 1993, the Administrative Group of the Rongelap Resettlement Project and the three scientists of the Scientific Management Team agreed to reprogram money from the "Plutonium in Urine" Study to make additional funds available for the "Child Trace Element Intake Study".

Since the beginning of the Rongelap Resettlement Project, progress has been made by Battelle Pacific Northwest Laboratories in increasing the sensitivity of ICPMS for measurement of plutonium or other heavy elements. As reported by Wyse and Fisher¹, the sensitivity of ICPMS has progressed such that detection limits are now similar or lower than that provided by conventional alpha spectrometry with much shorter sample measurement times. It is now claimed that the current technology under the best of circumstances may approach a sensitivity required to measure 4 to 8 μBq (100 to 200 aCi). This compares well to the average of 2 μBq (50 aCi) excreted daily per person as reported by BNL from measurements of Marshallese.

It is possible that a technology transfer in the future could make the ICPMS methodology for Pu measurements widely available. Private sector and/or public university laboratories could also conceivably contribute to the technology improvements needed. The availability of such technology would allow a contractor directly responsible to the Republic of the Marshall Islands or to the Rongelap Local Government perform the necessary measurements to verify that exposures remained acceptably low among the population resettling Rongelap Atoll.

¹Wyse, E.J. and D. R. Fisher. 1994. Radionuclide Bioassay by Inductively Coupled Plasma Mass Spectrometry (ICP/MS). *Radiation Protection Dosimetry*, 55 3:199-206.

APPENDIX A11

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Mr. James Matayoshi - RRP Administrative Director, Rongelap Atoll

Mr. Jeton Anjain (deceased) - Senator, Rongelap Atoll

Mr. Johnsay Riklong (replacement for Mr. Anjain) - Senator, Rongelap Atoll

Mr. Billiet Edmond - Mayor, Rongelap Atoll

Mr. Norio Kebinli (occasional replacement for Mr. Edmond)

Ms. Carmen Bigler - Secretary of Ministry of Internal Affairs

Mr. Methan Edwin (occasional replacement for Ms. Bigler)

Mr. Junior Nashion (occasional replacement for Ms. Bigler)

Mr. Wisse Amram (occasional replacement for Ms. Bigler)

Mr. Danny Jack (occasional replacement for Ms. Bigler)

Mr. Peter Oliver - Undersecretary for Compact Implementation, Ministry of Foreign Affairs

Mr. Hemos Jack - Secretary of Health, Republic of the Marshall Islands

Mr. Donald Capelle (replacement for Mr. Jack) - Secretary of Health and Environment, Republic of the Marshall Islands

Mr. Russel Edwards (occasional replacement for Mr. Capelle)

Mr. Hemos Jilej - Alab, Rongelap Atoll

Mr. Nicktemos Antak (occasional replacement for Mr. Jilej)